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Soil Survey Manual

Soil Science Division Staff

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By Soil Science Division Staff

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Introduction to the Fourth Edition

By Craig Ditzler, Kenneth Scheffe, and H. Curtis Monger, USDA–NRCS.

The *Soil Survey Manual,* USDA Handbook No. 18, provides the major principles and practices needed for making and using soil surveys and for assembling and using related data. The term "soil survey" is used here to encompass the process of mapping, describing, classifying, and interpreting natural three-dimensional bodies of soil on the landscape. This work is performed by the National Cooperative Soil Survey in the United States and by other similar organizations worldwide. The Manual provides guidance, methodology, and terminology for conducting a soil survey but does not necessarily convey policies and protocols required to administer soil survey operations. The soil bodies contain a sequence of identifiable horizons and layers that occur in repeating patterns in the landscape as a result of the factors of soil formation as described by Dokuchaev (1883) and Jenny (1941). Soil scientists gain an understanding of the factors of soil formation in their area, along with the resulting expression of their interaction in the soil, and are then able to make maps of the natural soil bodies quite efficiently (Hudson, 1992). The maps of soil bodies are related to, but different from, maps of single soil properties, such as organic matter or pH. The latter are made by sampling and statistical modeling to show how these properties vary over the landscape.

Purpose

The Manual is intended primarily for use by soil scientists engaged in the work of making soil surveys. It is an especially important reference for soil scientists early in their careers as they learn the many complex aspects of making a soil survey. It is also an important reference for experienced soil surveyors who want to review the details regarding many of the standards used in soil survey. For example, chapter 3, "Examination and Description of Soil Profiles," contains the accepted terms and definitions for specific soil properties that are used when describing soil profiles in the field. It also contains extensive information describing each soil property and the proper procedures for observing or measuring it in the field. The Manual is therefore an important companion to other soil survey references, such as the National Soil Survey Handbook (USDA-NRCS, 2016), the Field Book for Describing and Sampling Soils (Schoeneberger and Wysocki, 2012), and the Keys to Soil Taxonomy (Soil Survey Staff, 2014).

Although the Manual is oriented to the needs of those actively engaged in preparing soil surveys, workers and students who have limited soil science experience or are less familiar with the soil survey process can also use the information. Teachers, researchers, and students of soil science and related disciplines, especially those interested in pedology, soil morphology, soil geography, ecology, geomorphology, and the science underlying soil survey, will find this manual useful. Resource specialists, such as wetland scientists, foresters, and agronomists, and others who use soil surveys in their work, can refer to the Manual to better understand how soil surveys are made and how to interpret the technical information they provide. Parts of the Manual, especially those concerning the description of soils in the field and the soil properties considered when predicting soil behavior under a specific use, have been adopted by private-sector soil scientists as standards. The *Soil Survey Manual* has proven to be an important source of information for government agencies, nongovernmental organizations, and private-sector resource specialists in other countries involved in soil survey projects. Because the Manual describes all facets of the soil survey process, it is an important guide for developing proposals to conduct soil surveys and to create detailed plans for projects in other parts of the world.

The Manual serves as the guiding document for activities of the National Cooperative Soil Survey (NCSS), a cooperative undertaking led by the United States Department of Agriculture. The NCSS includes other Federal and State agencies, universities, non-governmental organizations, and private-sector soil scientists interested in making soil surveys and/or interpreting and using soil survey information. The original Federal authority for the Soil Survey of the United States is contained in the record of the 53rd Congress, Chapter 169, Agricultural Appropriations Act of 1896. The authority was elaborated in Public Law 74-46, the Soil Conservation Act of April 27, 1936, and again in Public Law 89-560, Soil Surveys for Resource Planning and Development, September 7, 1966. The Manual is the primary reference on the principles and technical details used by the local, State, and Federal contributors to soil surveys authorized under these acts.

Need for Additions and Revisions

Since the third edition (1993) of the Manual was printed, significant changes have occurred that affect the ways soil surveys are made. In the United States, greater emphasis is now placed on the maintenance and modernization of previously completed soil surveys. Because of this, some soil scientists are now evaluating and improving existing surveys rather than making new soil surveys. The wide application of computer technology, in both the office and the field, has led to a proliferation of electronic data sources, including digital elevation models (DEMs), Light Detection and Ranging (LiDAR), digital geology maps and vegetation maps, and multi-spectral remote sensing data. The electronic data sources, combined with computer models that capture and apply knowledge of the interaction of the soil-forming factors, have allowed soil scientists to partially, and in a few cases totally, automate the soil mapping process. This has had an important impact on the scientist's ability to formalize and document the soil-landscape models used to produce soil survey maps. It has also led to improved consistency in the maps produced using these methods. In addition, tools used for proximal sensing of soil properties, such as ground-penetrating radar and electromagnetic induction, have been increasingly used in special soil survey field studies. Greater attention is also being given to recognizing anthropogenic influences on soils. This has resulted in a need for the development of new standards for horizon nomenclature for human-altered soils, new terminology for describing human-made materials (artifacts) in soil profiles, and new classification groups. Soil surveys have also been conducted to a greater extent in shallow water (subaquatic) environments. New field procedures, descriptive terms, and taxonomic classes have been developed for conducting this innovative work.

Because of these changes, a major revision of the Manual was considered essential. Many parts have been revised, some parts have been extensively rewritten, and some new sections have been added. Entirely new subject matter in this edition of the Soil Survey Manual includes:

- Chapter 5, "Digital Soil Mapping." This chapter presents many concepts and principles that have been developed regarding the use of computers and digital technology to aid in the making of soil surveys.
- Chapter 6, "Tools for Proximal Soil Sensing." This chapter covers recent advances in the use of noninvasive tools for rapidly collecting information about soil properties.

- Chapter 9, "Assessing Dynamic Soil Properties and Soil Change." This chapter provides important information for documenting key soil properties, particularly in the near surface layers that are significantly impacted by soil management practices.
- Chapter 10, "Subaqueous Soil Survey." This chapter covers the emerging specialized field of making soil surveys in shallow water environments. This work is proving to be highly valuable to resource managers, especially in coastal estuarine environments.
- Chapter 11, "Human-Altered and Human-Transported Soils." This chapter provides valuable guidance on making soil surveys in environments heavily impacted by humans. Examples include urban areas, mined sites, and drastically changed soils used for agriculture.
- Appendices. The new appendices reflect the current form and content of web-accessible soil survey information in the United States. They are cross referenced in various places throughout the text.

Other significant revisions include:

- The former chapter 3 ("Examination and Description of Soils") is now split into two chapters: "Landscapes, Geomorphology, and Site Description" (chapter 2) and "Examination and Description of Soil Profiles" (chapter 3). This effectively separates the details for describing landscapes, geomorphology, and local site characteristics from the details for describing individual soil profiles. Both chapters incorporate all of the changes and additions to standard technical terms and their definitions that have been adopted by the National Cooperative Soil Survey since the previous publication of the Manual.
- The former chapters 2 ("Soil Systematics") and 4 ("Mapping Techniques") are combined and revised into a new chapter 4, "Soil Mapping Concepts." Information in the previous edition on procedures that have since become obsolete or nearly so (such as the use of stereoscopes and aerial photo pairs to visualize landforms in three dimensions, "color checking" to manually inspect maps for proper joining of units, and use of dot-grids to determine the aerial extent of map units) has been omitted.
- The former chapters 5 ("Information Recording and Management") and 7 ("Disseminating Soil Survey Information") are revised and updated into the new chapter 7, "Soil Survey Data Collection, Management, and Dissemination." The new chapter discusses the use of computer databases to effectively

store and manage soil survey information as well as provide information to end users. It also includes a historical summary of the development of the National Soil Information System (NASIS) in the United States. The summary may be useful to those outside the U.S. who are considering the development of a similar database.

- The former chapter 6 ("Interpretations") is revised and updated into the new chapter 8 ("Interpretations: The Impact of Soil Properties on Land Use"). The new chapter describes some of the latest strategies for making current interpretations more quantitative and providing interpretive information for anticipated uses.

Online Access

Given the rapid pace of technological change, flexibility is needed to provide information in a timely manner. In addition to a bound, hard-copy version of the *Soil Survey Manual,* a web-based version is also provided. The electronic version has convenient access and distribution of the information, and it affords users the option to "print on demand" individual parts or the entire document. The user can view each section of the Manual as a stand-alone chapter or view the entire document. The sections are arranged to correspond to the approximate chronological order of the work required to complete a soil survey. The reader has the choice of focusing on individual parts of interest or exploring the larger picture of conducting a soil survey project from beginning to end. Additional supplementary information not provided in the printed version will be included with the electronic version.

Citation and Authorship

The previous edition of the *Soil Survey Manual* (Soil Survey Division Staff, 1993) simply listed the author as the Soil Survey Division Staff. The contents of the Manual represented the collective contributions of many people over several decades. The new edition continues to recognize the innumerable past contributors by including the Soil Science Divison Staff as an author for chapters that retain significant portions of the previous publication. These chapters contain information that has been used for decades as well as new information related to improved methods and/or new terminology. For the updated chapters, authors responsible for revisions are listed in addition to the Soil Science Division Staff. For entirely new chapters, only individual contributing authors are cited by name. Technical content of the Manual was revised and edited by Craig Ditzler, Kenneth Scheffe, and H. Curtis Monger. English content was revised and edited by Jennifer Sutherland and Aaron Achen.

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CHAPTER 1

Soil and Soil Survey

By Soil Science Division Staff. Revised by Craig Ditzler and Larry West, USDA-NRCS.

This chapter describes the term "soil survey" within the context of the National Cooperative Soil Survey (NCSS) in the United States. It discusses the development of pedology and the important concept of soils as natural three-dimensional bodies that form as a result of the interaction of five soil-forming factors. The repeating patterns formed by these natural bodies of soil in the landscape allow soil scientists to develop predictive soil-landscape models, which serve as the scientific foundation for making soil surveys. Important milestones in the development of the Soil Survey in the United States are discussed at the end of this chapter.

Soil Survey—Definition and Description

A soil survey describes the characteristics of the soils in a given area, classifies the soils according to a standard system of taxonomy, plots the boundaries of the soils on a map, stores soil property information in an organized database, and makes predictions about the suitability and limitations of each soil for multiple uses as well as their likely response to management systems. The information collected in a soil survey helps in the development of land use plans and can be used to evaluate and predict the effects of land use on the environment.

A soil map consists of many individual delineations showing the location and extent of different soils. The collection of all delineations that have the same symbol on the map (e.g., 34B) are a "map unit." Each map unit is named for one or more soils or nonsoil areas (e.g., Sharpsburg silt loam). Each kind of soil or nonsoil (e.g., Rock outcrop) making up the composition of a map unit is a map unit component. See chapter 4 for a full discussion of map units and their components.

The soils are natural three-dimensional bodies occupying a characteristic part of the landscape. Soil survey maps are therefore different from other maps that show just one or a few specific soil properties or other environmental information. The concept of soil survey as defined for the NCSS is related to, but does not include, maps showing the distribution of a single soil property (such as texture, slope, or depth) alone or in limited combinations; maps showing the distribution of soil qualities (such as productivity or erodibility); and maps of soil-forming factors (such as climate, topography, vegetation, or geologic material). A soil map from a soil survey, as defined here, delineates areas occupied by different kinds of soil, each of which has a unique set of interrelated properties characteristic of the material from which it formed, its environment, and its pedogenic history. The soils mapped by the NCSS are identified by names that serve as references to a national system of soil classification.

The geographic distribution of many individual soil properties or soil qualities can be extracted from soil maps and shown on separate maps for special purposes, such as showing predicted soil behavior for a particular use. Numerous interpretative maps can be derived from a soil map, and each of these maps would differ from the others according to its purpose. A map made for one specific interpretation rarely can serve a different purpose.

Maps that show one or more soil properties can be made directly from field observations without making a basic soil map. Such maps serve their specific purposes but have few other applications. Predictions of soil behavior can also be mapped directly; however, most of these interpretations will need to be changed with changes in land use and in the cultural and economic environment. For example, a map showing the productivity of crops on soils that are wet and undrained has little value after drainage systems have been installed. If the basic soil map is made accurately, and a wide array of soil property data is collected and stored in an organized database, interpretative maps can be revised as needed without additional fieldwork. In planning soil surveys, this point needs to be emphasized. In some cases, inventories are made for some narrow objective, perhaps at a cost lower than that of a soil survey. Generally, maps for these inventories quickly become obsolete. They cannot be revised without fieldwork because vital data are missing, facts are mixed with interpretations, or boundaries between significantly different soil units have been omitted.

The basic objective of soil surveys is the same for all kinds of land, but the number of map units, their composition, and the detail of mapping vary with the complexity of the soil patterns and the specific needs of the users. Thus, a soil survey is designed for the soils and the soil-related problems of the area. Soil surveys increase general knowledge about soils and serve practical purposes. They provide soil information about specific geographic areas needed for regional or local land use plans. These plans include resource conservation for farms and ranches, development of reclamation projects, forest management, engineering projects, as well as other purposes.

Early Concepts of Soil

One of the earliest scholars of soils in the United States was Edmund Ruffin of Virginia. He worked diligently to find the secret of liming and discovered what is now called exchangeable calcium. After writing a brief essay in the *American Farmer* in 1822, he published the first edition of *An Essay on Calcareous Manures* in 1832. Much of what Ruffin learned about soils had to be rediscovered because his writings were circulated only in the South.

E.W. Hilgard was one of the first modern pedologists in the United States. His early concepts of soil (Hilgard, 1860, 1884, 1906) were based on ideas developed by the German chemist Justus von Liebig and modified and refined by agricultural scientists who worked on soil samples in laboratories, in greenhouses, and on small field plots. Soils were rarely examined below the depth of normal tillage. The chemists had a "balance-sheet" theory of plant nutrition. Soil was considered a more or less static storage bin for plant nutrients—the soils could be used and replaced. This concept still has value when applied within the framework of modern soil science, although a useful understanding of soils goes beyond the removal of nutrients from soil by harvested crops and their return to soil through manure, lime, and fertilizer.

Early geologists generally accepted the balance-sheet theory of soil fertility and applied it within the framework of their own discipline. They described soil as disintegrated rock of various sorts—granite, sandstone, glacial till, etc. However, they also described how the weathering processes modified this material and how geologic processes shaped it into landforms (such as glacial moraines, alluvial plains, loess plains, and marine terraces). N.S. Shaler's monograph on the origin and nature of soils summarized the late 19th century geological concept of soils (Shaler, 1891). Other details were added by G.P. Merrill (1906).

Near the end of the 19th century, Professor Milton Whitney inaugurated the National Soil Survey Program (Jenny, 1961). In the newly organized soil research unit of the U.S. Department of Agriculture, Whitney and his coworkers discovered great variations among natural soils—persistent variations that were in no way related to the effects of agricultural use. They emphasized the importance of soil texture and the capacity of the soil to furnish plants with moisture as well as nutrients. About this time, Professor F.H. King of the University of Wisconsin also reported the importance of the physical properties of soils (King, 1910).

Early soil surveys were made to help farmers locate soils responsive to different management practices and to help them decide what crops and management practices were most suitable for the particular kinds of soil on their farms. Many who worked on these early surveys were geologists because only geologists were skilled in the field methods and scientific correlation needed for the study of soils. They thought of soils as mainly the weathering products of geologic formations, defined by landform and lithologic composition. Most of the soil surveys published before 1910 were strongly influenced by these concepts. Those published from 1910 to 1920 were further refined and recognized more soil features but retained fundamentally geological concepts.

Early field workers soon learned that many important soil properties were not necessarily related to either landform or kind of rock. They noted that soils with poor natural drainage had different properties than soils with good natural drainage and that many sloping soils were unlike level ones. Topography was clearly related to soil profile differences. Soil structure was described in soil survey as early as 1902, in the soil survey of the Dubuque Area, Iowa (Fippin, 1902). The 1904 soil survey of Tama County, Iowa (Ely et. al., 1904) reported that soils that had formed under forest contrasted markedly with other soils that had similar parent material but formed under grass.

Soils as Natural Bodies

The balance-sheet theory of plant nutrition dominated laboratory work, while the geological concept dominated fieldwork. Both approaches were taught in many classrooms until the late 1920s. Although broader and more generally useful concepts of soil were being developed by some soil scientists, especially Hilgard (1860) and Coffey (1912) in the U.S. and soil scientists in Russia, the necessary data for formulating these broader concepts came from the fieldwork of the Soil Survey during the first decade of its operations in the United States. The concept of the solum and the A-B-C horizon nomenclature were becoming central to pedology and soil survey (Tandarich et al., 2002). After the work of Hilgard, the most significant advance toward a more satisfactory concept of soil was made by G.N. Coffey. Coffey determined that the ideal classification of soil was a hierarchical system based on the unique characteristics of soil as "a natural body having a definite genesis and distinct nature of its own and occupying an independent position in the formations constituting the surface of the earth" (Cline, 1977).

Beginning in 1870, the Russian school of soil science under the leadership of V.V. Dokuchaev and N.M. Sibertsev was developing a new concept of soil. The Russian scientists conceived of soils as independent natural bodies, each with unique properties resulting from a unique combination of climate, living matter, parent material, relief, and time (Gedroiz, 1925). They hypothesized that properties of each soil reflected the combined effects of the particular set of genetic factors responsible for the soil's formation, emphasizing the importance of the "zonal" concept (i.e., the bioclimatic zone in which the soil formed). Hans Jenny later emphasized the functional relationships between soil properties and soil formation. The results of this work became generally available to Americans through the publication in 1914 of K.D. Glinka's textbook in German and especially through its translation into English by C.F. Marbut in 1927 (Glinka, 1927).

The Russian concepts were revolutionary. Soil properties were no longer based wholly on inferences from the nature of rocks or from climate or other environmental factors, considered singly or collectively. Instead, the integrated expression of all these factors could be seen in the morphology of the soils. This concept required that *all properties* of soils be considered collectively in terms of a completely integrated natural body. In short, it made possible a science of soil.

As a result of the early enthusiasm for the new concept and for the rising new discipline of soil science, some suggested that the study of soil could proceed without regard to the older concepts derived from geology and agricultural chemistry. Certainly, the reverse was true. Besides laying the foundation for a soil science with its own principles, the new concept made the other sciences even more useful. Soil morphology provides a firm basis on which to group the results of observation, experiments, and practical experience and to develop integrated principles that predict the behavior of soils.

Under the leadership of C.F. Marbut, the Russian concept was broadened and adapted to conditions in the United States (Marbut, 1921). As mentioned earlier, this concept emphasized individual soil profiles and subordinated external soil features and surface geology. By emphasizing soil profiles, however, soil scientists initially tended to overlook the natural variability of soils, which can be significant even within a small area. Overlooking the variability of soils seriously reduced the value of maps that showed the location of soils. This weakness soon became evident in the U.S., perhaps because of the emphasis on making detailed soil maps for their practical, predictive value. Progress in transforming the profile concept into a more reliable predictive tool was rapid because a large body of important field data had already been accumulated. By 1925, a large amount of morphological and chemical work was being done on soils throughout the country. The data collected by 1930 were summarized and interpreted in accordance with this concept, as viewed by Marbut in his work on the soils of the United States (Marbut, 1935).

Early emphasis on genetic soil profiles was so great as to suggest that material lacking a genetic profile, such as recent alluvium, was not soil. A sharp distinction was drawn between rock weathering and soil formation. Although a distinction between these sets of processes is useful for some purposes, rock and mineral weathering and soil formation commonly are indistinguishable.

The concept of soil was gradually broadened and extended during the years following 1930, essentially through consolidation and balance. The major emphasis had been on the soil profile. After 1930, morphological studies were extended from single pits to long trenches or a series of pits in an area of a soil. The morphology of a soil came to be described by ranges of properties deviating from a central concept instead of by a single "typical" profile. The development of techniques for mineralogical studies of clays also emphasized the need for laboratory studies.

The clarification and broadening of soil science also was due to the increasing emphasis on detailed soil mapping. Concepts changed with increased emphasis on predicting crop yields for each kind of soil shown on the maps. Many of the older descriptions of soils had not been quantitative enough and the units of classification had been too heterogeneous to use in making the yield and management predictions needed for planning the management of individual farms or fields.

During the 1930s, soil formation was explained in terms of loosely conceived processes, such as "podzolization," "laterization," and "calcification." These were presumed to be unique processes responsible for the observed common properties of the soils of a region (Jenny, 1946).

In 1941, Hans Jenny's *Factors of Soil Formation*: *A System of Quantitative Pedology* concisely summarized and illustrated many of the basic principles of modern soil science to that date (Jenny, 1941). Since 1940, time has assumed much greater significance among the factors of soil formation and geomorphological studies have become important in determining the time that soil material at any place has been subjected to soil-forming processes. Meanwhile, advances in soil chemistry, soil physics, soil mineralogy, and soil biology, as well as in the basic sciences that underlie them, have added new tools and new dimensions to the study of soil formation. As a consequence, the formation of soil has come to be treated as the aggregate of many interrelated physical, chemical, and biological processes. These processes are subject to quantitative study in soil physics, soil chemistry, soil mineralogy, and soil biology. The focus also has shifted from the study of gross attributes of the whole soil to the co-varying detail of individual parts, including grain-to-grain relationships.

Early Development of Soil Classification

C.F. Marbut strongly emphasized that the classification of soils should be based on morphology instead of on theories of soil genesis, because theories are both ephemeral and dynamic. He perhaps overemphasized this point because some scientists assumed that soils had certain characteristics without ever actually examining them. Marbut stressed that examination of the soils themselves was essential in developing a system of soil classification and in making usable soil maps. However, Marbut's work reveals his personal understanding of the contributions of geology to soil science. His soil classification of 1935 relied heavily on the concept of a "normal soil," the product of equilibrium on a landscape where downward erosion keeps pace with soil formation. Continued work in soil classification by the U.S. Department of Agriculture culminated in the release of a new system published in the 1938 Yearbook of Agriculture in the chapter "Soil Classification" (Baldwin et al., 1938).

In both the early classification developed by Marbut and the later 1938 classification developed by USDA, the classes were described mainly in qualitative terms. Because the central concept of each class was described but the limits between classes were not, some soils seemed to be members of more than one class. The classes were not defined in quantitative terms that would permit consistent application of the system by different scientists. Neither system definitely linked the classes of its higher categories, which were largely influenced by the genetic concepts initiated by the Russian soil scientists, to the soil series and their subdivisions that were used in soil mapping in the United States. Both systems reflected the concepts and theories of soil genesis of the time, which were themselves predominantly qualitative in character. Modification of the 1938 system in 1949 corrected some deficiencies but also illustrated the need for a reappraisal of concepts and principles. One continuing problem was that a scientist required knowledge about the genesis of the soil to classify it. This information was often lacking or was disagreed upon by soil surveyors. It was determined that a new classification system was required, one that could be applied consistently by an increasingly large and varied cadre of soil surveyors.

Modern Concept of Soil

Soil as defined in *Soil Taxonomy* (Soil Survey Staff, 1999) is "a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment."

The "natural bodies" of this definition include all genetically related parts of the soil. A given part, such as a cemented layer, may not be capable of supporting plants. However, it is still a part of the soil if it is genetically related to the other parts and if the body as a unit is either capable of supporting plants or has horizons or layers that are the result of the pedogenic processes, i.e., additions, losses, transfers, and transformations (Simonson, 1959). Nearly all natural bodies recognized as "soil" are capable of supporting plants. Some that cannot support higher plants are still recognized as soil because they are affected by pedogenic development. Soils in very harsh environments, such as Antarctica, are an example. The definition of soil also includes natural bodies that are capable of supporting plants even though they do not have genetically differentiated parts. For example, a fresh deposit of alluvium or earthy constructed fill is soil if it can support plants.

Bodies of water that support floating plants, such as algae, are not considered soil because these plants are not rooted. However, the sediment below shallow water is soil if it can support bottom-rooting plants (such as cattails, reeds, and seaweed) or if the sediment exhibits changes due to pedogenic processes. These soils are commonly referred to as "subaqueous soils" (see chapter 10). The above-ground parts of plants are also not soil, although they may support parasitic plants. Also excluded is rock that mainly supports lichens on the surface or plants only in widely spaced cracks.

The transition from nonsoil to soil can be illustrated by recent lava flows in warm regions under heavy and very frequent rainfall. In those climates, plants become established very quickly on the basaltic lava, even though there is very little earthy material. They are supported by the porous rock filled with water containing plant nutrients. The dominantly porous, broken lava in which plant roots grow is soil.

Marbut's definition of soil as "the outer layer" of the Earth's crust implied a concept of soil as a continuum (Marbut, 1935). The current definition refers to soil as a collection of natural bodies on the surface of the Earth. It divides Marbut's continuum into discrete, defined parts that can be treated as members of a population. The perspective of soil has changed from one in which the whole was emphasized and its parts were loosely defined to one in which the parts are sharply defined and the whole is an organized collection of these parts.

Development of Soil Taxonomy

More than 15 years of work under the leadership of Dr. Guy Smith culminated in a new soil classification system. Categories and classes of the new taxonomy were direct consequences of new and revised concepts and theories. This system became the official classification system of the U.S. National Cooperative Soil Survey in 1965 and was published in 1975 as *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys* (Soil Survey Staff, 1975). The system's most significant contribution was the establishment of taxonomic class limits and their quantitative definitions, whereby an individual soil could belong to only one class. Soil genesis was no longer used directly in determining the correct classification. Instead, diagnostic horizons and features that are the morphological expression of major known genetic processes were defined and used. In this way the current understanding of soil genesis, while indirectly incorporated in the taxonomy, is one step removed from the process of classifying a soil (Smith, 1963). The application of quantitative diagnostic horizons and features as criteria to be used in soil classification has been widely adopted in other soil classification systems around the world, perhaps most notably by the World Reference Base (IUSS Working Group WRB, 2014), sponsored by the Food and Agriculture Organization of the United Nations.

The system of soil classification discussed in *Soil Taxonomy* is dynamic and can change as new knowledge is obtained. The theories on which the system is based are tested every time the taxonomy is applied. During the 1980s and 1990s, nine international committees contributed to major revisions of the taxonomy. This work culminated in the printing of the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999). In addition, many individual proposals for change have been incorporated in editions of the *Keys to Soil Taxonomy,* which have been published periodically since the first edition of *Soil Taxonomy* was published in 1975. The work of a 10th international committee, which addressed the impact of human influences on soils, resulted in important changes. These changes are reflected in the 12th edition of the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014).

Scientific Foundation of Soil Survey

Soil survey is grounded in scientific principles that can be described by the factors of soil formation and by the relationships between landscapes, landforms, and soils. The soil-forming factors are responsible for the genetic development of soil profiles. The relationships between landscapes, landforms, and soils are used to understand the predicable patterns of natural soil bodies in the landscape.

Factors that Control the Distribution of Soils

The properties of soil vary from place to place, but this variation is not random. Natural soil bodies are the result of climate and living organisms acting on parent material, with topography or local relief exerting a modifying influence and with enough time for soil-forming processes to act. For the most part, soils are the same wherever all elements of the five factors are the same. Under similar environments in different places, soils are similar. This regularity permits prediction of the location of many different kinds of soil. This fundamental principle makes soil survey practical (Hudson, 1992).

When soils are studied in small areas, the effects of topography (or local relief), parent material, and time on soil become apparent. In humid regions, for example, wet soils and the properties associated with wetness are common in low-lying places while better drained soils are common in higher lying areas. The correct conclusion to draw from these relationships is that *topography* or *relief* is important. In arid regions, the differences associated with relief may be manifested in variations in salinity or sodicity, but the conclusion is the same. In a local environment, different soils are associated with contrasting parent materials, such as residuum from shale and residuum from sandstone. The correct conclusion to draw from this relationship is that *parent material* is important. Soils on a flood plain differ from soils on higher and older terraces where there is no longer deposition of parent material on the surface. The correct conclusion to draw from this relationship is that *time* is important. The influence of topography, parent material, and time on the formation of soil is observed repeatedly while studying the soils of an area.

With the notable exception of the contrasting patterns of vegetation in transition zones, local differences in vegetation are closely associated with differences in relief, parent material, or time. The effects of microclimate on vegetation may be reflected in the soil, but such effects are likely associated with differences in local relief.

Regional climate and vegetation influence the soil as well as topography/relief, parent material, and time. In spite of local differences, most of the soils in an area typically have some properties in common, which reflect the soil-forming factors influencing the soils regionally. The low-base status of many soils in humid regions or regions with naturally acid rock or sediment stands in marked contrast to the typical high-base status in arid regions or regions with calcareous sandstone or limestone. In old landscapes of humid regions, however, low-base status is so commonplace that little significance is attached to it when considered only from the narrow perspective of old landscapes in a humid region alone.

Regional patterns of climate, vegetation, and parent material can be used to predict the kinds of soil in large areas. The local patterns of topography/relief, parent material, and time, and their relationships to vegetation and microclimate, can be used to predict the kinds of soil in small areas. Soil surveyors learn to use local features, especially topography and associated vegetation, as indicators of unique combinations of all five soil-forming factors. These features are used to predict boundaries of different kinds of soil and to predict some of the properties of the soil within those boundaries.

Soil-Landscape Relationships

Geographic order suggests natural relationships. For example, weathering and erosion of bedrock by running water commonly sculpt landforms within a landscape. Over the ages, earthy material has been removed from some landforms and deposited on others. Landforms are interrelated. An entire area has unity through the interrelationships of its landforms.

Each distinguishable landform may have one kind of soil or several. Climate, including its change over time, commonly will have been about the same throughout the extent of a minor landform. In addition, the kinds of vegetation associated with climate will likely have been fairly uniform. Relief varies within some limits that are characteristic of the landform. The time that the material has been subjected to soil formation will probably have been about the same throughout the landform. The surface of the landform may extend through one kind of parent material and into another. Of course, position on the landform may have influenced soil-water relationships, microclimate, and vegetation.

Just as different kinds of soil are commonly associated in a landscape, several landscapes are commonly associated in still larger areas. These areas cover thousands or tens of thousands of square kilometers. Many can be identified on photographs taken from satellites. From this vantage point, broad physiographic regions are apparent. Examples in the U.S. are the East Gulf Coastal Plain, the Appalachian Plateau, the Wyoming Basin, and the Great Plains. These broad units typically have some unity of landscape, as indicated by such terms as “plain,” “plateau,” and “mountain.” These physiographic units are composed of many kinds of soil.

The main relief features of a physiographic unit are commonly the joint products of deep-seated geologic forces and a complex set of surface processes that have acted over long spans of time. Within a physiographic unit, groups of minor landforms are shaped principally by climate-controlled processes. The climate and biological factors, however, vary much less within a geomorphic unit than across a continent.

Still broader than the geomorphic units are great morphogenetic regions that have distinctive climates. For example, one classification recognizes glacial, periglacial, arid, semiarid-subhumid, humid-temperate, and humid-tropical climatic regions associated with distinctive sets of geomorphic processes. Other major regions are characterized by seasonal climatic variation. These geomorphic-climatic regions are related to soil moisture and soil temperature regimes. Thus, the great climatic regions are divided into major physiographic units. Landscapes and associated landforms are small parts of these units and are commonly of relatively recent origin.

The landforms important in soil mapping may include constructional units, such as glacial moraines and stream terraces, and elements of local sequences of graded erosional and constructional land surfaces. These bear the imprint of local, base-level controls under climate-induced processes. Most surfaces that have formed within the last 10,000 years have been subject to climatic and base-level controls similar to those of the present. Older surfaces may retain the imprint of climatic conditions and related vegetation of the distant past. Most present-day landforms started to form during the Quaternary period; some started in the late Tertiary period. In many places, conditions of the past differed significantly from those of the present. Understanding climatic changes, both locally and worldwide, into the far past contributes to understanding the attributes of present-day landforms.

Geomorphic processes are important in mapping soils. Soil scientists need a working knowledge of local geomorphic relationships in areas where they map. They should also understand the interpretations of landforms and land surfaces made by geomorphologists. The intricate interrelationships of soil and landscape are best studied by collaboration between soil scientists and geomorphologists. Standards and protocols for describing landscapes and geomorphology are discussed in chapter 2.

Development of the Soil Survey in the U.S.

Soil surveys were authorized in the United States by the U.S. Department of Agriculture Appropriations Act for fiscal year 1896, which provided funds for an investigation "of the relation of soils to climate and organic life" and "of the texture and composition of soils in field and laboratory." In 1966, Congress expanded the scope of the Soil Survey Program and further clarified its intent in Public Law 89-560, the Soil Survey for Resource Planning and Development Act. This legislation recognized that soil surveys are needed by States and other public agencies to support community planning and resource development in order to protect and improve the quality of the environment, meet recreational needs, conserve land and water resources, and control and reduce pollution from sediment and other pollutants in areas of rapidly changing uses.

Many soil surveys have been initiated, completed, and published cooperatively by the U.S. Department of Agriculture, State agencies, and other Federal agencies. The total effort is the National Cooperative Soil Survey (NCSS). The NCSS is a nationwide partnership of Federal, regional, State, and local agencies and private entities and institutions. This partnership works to cooperatively investigate, inventory, document, classify, interpret, disseminate, and publish information about soils of the United States and its trust territories and commonwealths.

The following discussion highlights some of the important developments that helped shape the U.S. soil survey over its more than 100-year history.

1896 to 1920

In 1899, the U.S. Department of Agriculture completed field investigations and soil mapping of portions of Utah, Colorado, New Mexico, and Connecticut. Reports of these soil surveys and similar works were published by legislative directive. At the same time, the State of Maryland, using similar procedures and State funds, completed a soil survey of Cecil County.

The early soil surveys investigated the use of soils for farming, ranching, and forestry. Eventually, soil survey data began to be applied to other uses, such as highways, airfields, and residential and industrial developments. As more surveys were made and their use expanded, the knowledge about soils—their nature, occurrence, and behavior for defined uses and management—also increased. The Highway Department of Michigan was applying soil survey data and methods in planning highway construction in the late 1920s. At about the same time, soil surveys in North Dakota were being used in tax assessment.

1920 to 1950

Soil surveys published between 1920 and 1930 reveal a marked transition from earlier concepts that emphasized soil profiles and soils as independent bodies. The maps retained significant geologic boundaries as soil maps do today. Many of the surveys of that period provide excellent general maps for evaluating engineering properties of geologic material. In addition, maps and texts of the period show more recognition of other soil properties significant to farming and forestry than do earlier surveys and have value for broad generalizations about farming practices in large areas. To meet the needs of planning the management of individual fields and farms, greater precision of interpretation was required. The changing objectives of soil surveys initiated changes in methods and techniques that would make surveys more useful and forced scientists to reconsider the concept of soil itself.

Beginning in the 1930s, the Soil Conservation Service (SCS) emphasized the control of soil erosion as it used soil surveys for the resource conservation planning of farms and ranches. In the 1950s, soil survey information was used extensively in urban land development in Fairfax County, Virginia, and in the subdivision design of suburban areas of Chicago, Illinois. Soil surveys were an important base for resource information in regional land use planning in southeastern Wisconsin. Rural land zoning also relied on soil surveys.

Several other advancements contributed to the expansion and increased precision of soil survey. An early change was the use of aerial photographs as base maps in detailed soil mapping during the late 1930s and early 1940s. Aerial photos served not only as base maps that improved the surveyor's ability to locate their positions in the field but also were used in stereo pairs to view the landscape in three dimensions.

The use of stereo pairs greatly enhanced the surveyor's ability to place soil boundaries correctly in relation to position on the landform.

Before 1950, the primary applications of soil surveys were farming, ranching, and forestry. Applications for highway planning were recognized in some States as early as the late 1920s, and soil interpretations were placed in field manuals for highway engineers of some States during the 1930s and 1940s. However, the changes in soil surveys during this period were mainly responses to the needs of farmers, ranchers, and forest managers.

1950 to 1970

During the 1950s and 1960s, nonfarm uses of the soil increased rapidly. This created a great need for information about the effects of soils on these nonfarm uses. Beginning around 1950, cooperative research with the Bureau of Public Roads and with State highway departments established a firm basis for applying soil surveys to road construction. The laboratories of many State highway departments assisted soil survey operations by characterizing soils for properties such as particle-size distribution, plasticity index, and liquid limit in order to determine their proper placement in engineering classification systems. Soil scientists, engineers, and others worked together to develop interpretations of soils for roads and other nonfarm uses. These interpretations, which have become standard parts of published soil surveys, require different information about soils. Some soil properties that are not important for plant growth are very important for building sites, sewage disposal systems, highways, pipelines, and recreational development. Because many of these uses of soil require very large capital investments per unit area, errors can be extremely costly. Consequently, the location of soil boundaries, the identification of the delineated areas, and the quantitative definition of map units have assumed great importance.

In 1966, the Soil Survey for Resource Planning and Development Act recognized the expanding role of soil survey in supporting efforts to protect and improve the environment. It led to increased efforts to provide technical assistance in the use of soil survey information for land use planning, conservation, and development activities.

1970 to 2000

The use of aerial photography in soil survey was further enhanced by the introduction of orthophotography for the base map in publications. Aerial photographs contain inherent cartographic distortion and are therefore not true to scale across all parts of the image. Orthophotographs are digitally rectified to correct the spatial relationship of locations on the photo. Therefore, they provide a cartographically accurate base map to which field-drawn boundaries can be transferred. This advancement, coupled with advances in computer technology, soon led to the proliferation of digitized soil surveys throughout the 1990s and early 2000s. These surveys became widely available for use in geographic information systems (GIS) and over the Internet. Combining soil survey data with other resource and cultural data layers in a GIS greatly enhanced the ways in which soil survey information could be used.

The adoption of Soil Taxonomy in 1975 as the official system for classifying soils in the U.S. (discussed above) had several important effects on soil survey. Through the use of quantitative class limits and diagnostic horizon definitions, all soil scientists, regardless of experience, were now able to classify soils correctly and consistently. Because of the need for data to properly classify the soil, the quality of field morphological descriptions was enhanced and efforts to obtain data measured in the laboratory increased. The use of Soil Taxonomy also improved the process of correlating soils from one soil survey project to another.

From the 1970s onward, much emphasis was devoted to the development of automated systems to store observations and manage data and interpretations, culminating in the National Soil Information System (NASIS). In addition, many soil surveys were digitized and made available electronically for use in geographic information systems. The development of digital soil information is discussed in greater detail in chapter 7.

In the mid-1970s, a new and important interest in soil survey emerged. The U.S Fish and Wildlife Service was charged with developing a wetland inventory of the United States. It partnered with the Soil Survey Division of the Soil Conservation Service to develop the concept and definition of "hydric soils" in support of the broader definition used to identify wetland areas for the inventory. Many established soil series were identified as likely to meet the definition of a hydric soil. The areas shown on soil survey maps that are composed of these soils were considered likely wetland areas for inclusion in the National Wetland Inventory. The soil survey became an important tool, along with other sources of hydrologic and vegetative information, for identifying wetlands for the inventory. A decade later, as a result of the Farm Bill passed by Congress in 1985, the demand for soil survey information increased further with the need to support the environmentally important "Swamp Buster" and "Sod Buster" provisions of the legislation. The soil survey maps and information were crucial for identifying hydric soil areas as well as areas considered to be "highly erodible." As a result, soil survey has been a major supporter of national efforts to protect and enhance the Nation's resources.

2000 and Onward

More recent efforts (since about 2000) to digitize all soil surveys and make them widely available through Internet access via the Web Soil Survey (Soil Survey Staff, 2016) have led to yet greater use of and demand for soil survey information for an ever wider group of users (see appendices). Now that users have electronic access to soil survey maps and information, the demand for hard-copy soil survey reports has decreased (see chapter 7 for a fuller discussion).

In addition to aerial photography, a wealth of multi-spectral data sources from airborne platforms and satellites have provided a wide range of remotely sensed information that can be used to infer the kinds and influence of soil-forming factors in digital soil mapping efforts (discussed in chapter 5). Noninvasive field tools, such as ground-penetrating radar, electromagnetic induction, portable X-ray fluorescence, and other proximal sensing technologies, also are being used to rapidly assess soil properties. These tools are discussed in greater detail in chapter 6.

A series of specialized interpretations have been developed for use by emergency response agencies. Soil information can be useful in providing rapid response to natural disasters and other civil emergencies. For example, it can be used to address oil spills or mass animal mortality in the agricultural sector (such as by avian flu) and the need to dispose of carcasses safely.

In the United States, after more than 100 years of soil survey work, nearly all of the Nation's lands have been surveyed. The emphasis is no longer on making soil surveys where none existed but on maintaining and modernizing existing soil surveys. Technology and standards have evolved, and the kinds of information needed have changed. In addition, there remains an ongoing effort to better coordinate and join the individual soil surveys over large areas. The NCSS program is focused upon completing soil surveys for the few remaining unmapped areas and coordinating and updating existing soil surveys through correlation activities and data collection. It provides a cadre of trained soil scientists to assist soil survey users with the application of soil survey information for land resource management. The four fundamental goals guiding the NCSS program are: (1) completing the inventory of soils in the United States, (2) keeping the inventory current, (3) providing interpretive information about the soils, and (4) providing access to and promoting use of soil information. The NCSS motto is “Helping people understand soils.”

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CHAPTER 2

Landscapes, Geomorphology, and Site Description

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Introduction

This chapter describes information that is recorded about the overall setting and site features for a soil. This information includes the physiographic and landscape setting, geomorphological characteristics, and other information specific to the area where the soil is described. The setting and site often include information on drainage pattern, parent material, bedrock, erosion, land cover, and relationships to vegetation communities. Detailed information about describing soil profiles is provided in chapter 3.

A core mission of the National Cooperative Soil Survey (NCSS) of the United States is to reliably identify, inventory, and communicate information about soils and the earth systems of which they are a part. The Earth's surface, including the soils upon it, forms an ordered but complex mosaic, consisting of many pieces of different sizes, shapes, origins, and composition. It is a very human thing to try to make sense of this mosaic by identifying recurring patterns and to separate pieces into groups with similar form, content, and function. Depending upon a person's perspective and goals, there are infinite ways to partition the Earth's surface into meaningful subsets. A person interested in agriculture will have different management goals and examine different site criteria than someone interested in construction. The initial perspective will determine which variables are important to highlight, which can be grouped together, and which need to be separated. The NCSS has traditionally been based on multipurpose perspectives and goals that integrate aspects of agriculture, forestry, engineering applications, animal husbandry, and, in recent decades, ecosystem function and environmental sustainability. These multiple perspectives led to an assemblage of descriptive criteria and protocols rooted in earth science that were later expanded to address ecosystems and human-altered settings and features.

Geology

Among the many perspectives that can be applied, geology provides the most reliable and robust context for understanding natural earth systems, including soils, across the widest range of environments. It is a perspective that recognizes and details the primary framework upon which natural processes and humans operate. Geology largely defines the material architecture of the soil, i.e., the composition, general arrangement, and lateral extent of these materials. It helps to explain the configuration and distribution of the materials of which the soil is composed.

Geomorphology

Geomorphology is the study of landforms, the materials of which they are made, and the dynamics by which they are made and function. It is at the center of understanding what earth materials are, how they interact, how they originated, and how far they extend and where similar conditions and materials are likely to occur. It focuses on the combinations of composition, stratigraphy, shape, and topography of the materials and the geologic processes that give rise to and modify them.

Soil Geomorphology

Soil geomorphology addresses geomorphic details and dynamics at and near the Earth's surface that affect, or are affected by, soil processes and products. It specifically addresses the distribution, properties, and dynamic behavior of soils—issues that traditional geology and geomorphology do not emphasize because of scale or minimize because of perspective. These soil issues are particularly environmentally and economically meaningful because they occur at the "human-operative scale," i.e., the scale at which most land use decisions are made and applied and their consequences felt.

Soil science, particularly soil geomorphology, is based upon a robust relationship between lithology, hydrology, stratigraphy, geomorphology, and, to a slightly lesser degree, biota and climate (Wysocki et al., 2012; Schaetzl and Thompson, 2014; Buol et al., 2011). In many settings, hydrology and hydropedology dominate the physical redistribution of materials and catalyze the chemical reactions that transform earth materials (Simonson, 1959; Lin, 2012).

Boundaries and Transitions

Some parts of the landscape and the soils on them are separated from their neighbors by distinct, sharp boundaries over a lateral distance of just meters. For example, a stream terrace may be sharply separated from adjacent cliffs and talus cones by an abrupt, easily observed scarp (fig. 2-1). Other parts of the landscape and the soils on them have lateral boundaries that are very gradual and indistinct, transitioning over tens of meters or kilometers. For example, a loess mantle thins gradually with increasing distance from the source of the loess.

Figure 2-1

Distinct, sharp breaks between landforms are evident over short lateral distances, as shown by the talus cone in this canyon along the Palouse River in Washington.

Scale

Another major determinant in conveying soil and geomorphic information is the scale of interest (e.g., local, regional, global), which is established in initial survey perspectives and goals. Scale partly predetermines what is "relevant" and what is not, what must be "shown" and what cannot. A person managing a 1-hectare homesite has different information needs and relevancies than a regional planner who evaluates and manages a city or State. The scale of interest can be quite different for different users, and the appropriate level of information to be collected and delivered differs with the scale. At regional scales, it is typically appropriate to evaluate and emphasize landscapes and very large, constituent landforms and to minimize smaller landforms and micro-features. For example, in an order 3 reconnaissance survey, dune fields, mountain ranges, or bolsons may be evaluated. Conversely, for localized surveys, it is typically necessary to focus primarily on smaller landforms, microfeatures, or pieces of landforms and to give only nominal attention to landscapes. For example, in an order 1 survey, barchan dunes, slip faces, or head slopes may be evaluated. The provisional soil survey of the Outer Banks of North Carolina, at a scale of 1:12,000 (USDA-SCS, 1977) is an example of a localized survey that presents the setting in considerable detail.

Digital Soil Mapping and Scale

Widely available GIS tools and digital soil mapping methods have made it much easier to move between scales. For example, geospatial information that was previously constrained by scale may be combined or split apart (see chapter 5). It is now possible to produce: (a) primary surveys capable of spanning a much wider range of scale, and (b) derivative or second-generation resource maps from a primary spatial database that span wider ranges of scale than the initial survey. The capability to move between scales must coincide with primary data that accommodates such changes in scale. For example, traditional soil inventories were made based upon stated, relatively narrow spatial scales (e.g., order 2 or 3). The initial field data collected, assigned classes, spatial separations (e.g., polygons), interpretations, and other information remain constrained by the rules and decisions for the scale at which they were originally developed. It is typically possible to aggregate data upwards in scale with a minimal impact on information integrity. It is much more challenging to do the opposite and legitimately disaggregate primary data to create finer resolution information. With new tools, software, and statistical methods, it is possible to produce information with finer resolution using disaggregation techniques. However, the original data, metadata, and inherent decisions made at the original inventory scale remain determinate; those original biases will persist across scales. Some morphometric parameters, such as slope, can be readily replaced or enhanced with higher resolution information, such as LiDAR. In some cases, such as the separation of soil bodies at finer resolution, previous information can be more problematic and new supporting data appropriate to the new scale may be needed.

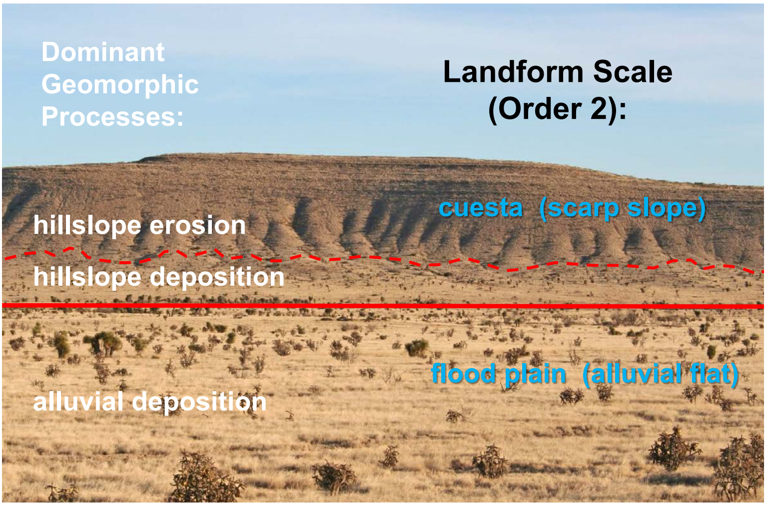
Capturing Soil-Landscape Relationships at Various Scales

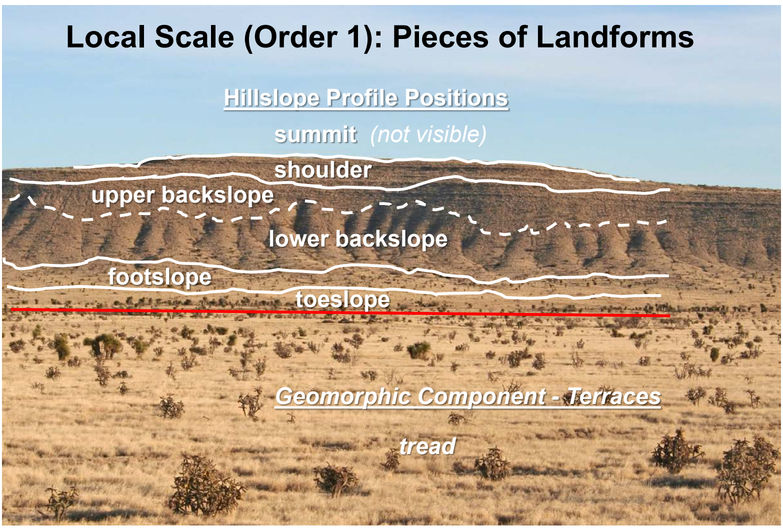
It is typically impractical or financially prohibitive to make an ideal number of field observations. Consequently, representative observation sites need to be chosen wisely and used to extrapolate to areas that cannot be visited. Observation efficiency can be greatly enhanced by developing soil-landscape models that capture recurring spatial relationships. Part of such model development includes selecting an appropriate scale. As discussed previously, scale determines what can and cannot be shown. Robust soil-landscape models are subject to incremental changes and refinements that reflect the accumulation of knowledge and data during the progression of the survey.

A site may have one of three common scales of models: a large area or catchment (landscape) scale, a hill (landform) scale, and a hillslope position or pedon (microfeature) scale. The appropriateness of each scale depends upon the perspectives and objectives of the survey. Each scale can be applied, but each conveys somewhat different information and has different strengths and limitations. For example, for a setting along the border of the Gypsum Plains State Physiographic Area in Culberson County, Texas, a series of hierarchical (nested) landscape models can be developed and applied. At a landscape scale, the area presents eroded structural hills and alluvial plains. The dominant geomorphic processes are tectonic and erosional (and, to a minor extent, fluvial) and are regional in scope. At a landform scale (fig. 2-2, top image), which is finer than landscape, the same area presents an eroded, structural hill (questa) and valley floor (alluvial flat). The dominant geomorphic processes are erosional and fluvial and are local in scope. At a microfeature scale (fig. 2-2, bottom image), the area presents discrete subsets within landforms. The dominant geomorphic processes are hillslope erosion and deposition (slope wash processes) and fluvial modification (alluvial deposition processes) and are very localized in scope. Different scales yield different information.

Hillslope-scale processes commonly express themselves differently at different positions (i.e., summit, shoulder, upper slope or backslope, footslope, and toeslope). Each hillslope position represents a process-dominated area, as demonstrated by a progressive reduction of rock fragment size across the ground surface from the summit to the toeslope position (fig. 2-3).

Figure 2-2





A scarp slope of a cuesta above an alluvial flat. Scale determines which geomorphic descriptors can be effectively used and presented. Geomorphic evaluations of regional scope (landscape scale) can separate tectonic hills from areas dominated by fluvial processes (not shown). The more localized, landform scale can differentiate dominant landforms (cuesta and alluvial flat) and the dominant geomorphic processes that control them within the landscape (top image). More detailed erosional and depositional surfaces derived from dominant hillslope processes need to be represented at a finer scale. These include microfeatures (e.g., ribs and groves), hillslope profile positions (e.g., summits and shoulders), and geomorphic components (e.g., components of terraces or hills, such as nose slopes, head slopes, and side slopes; not shown).

Figure 2-3

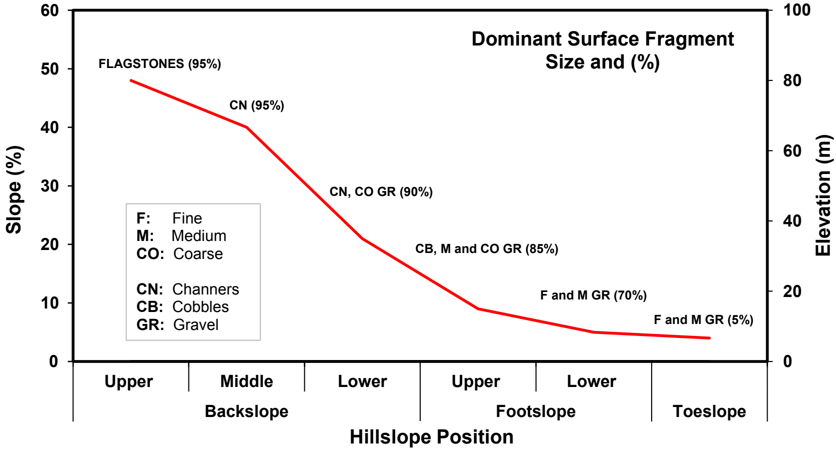
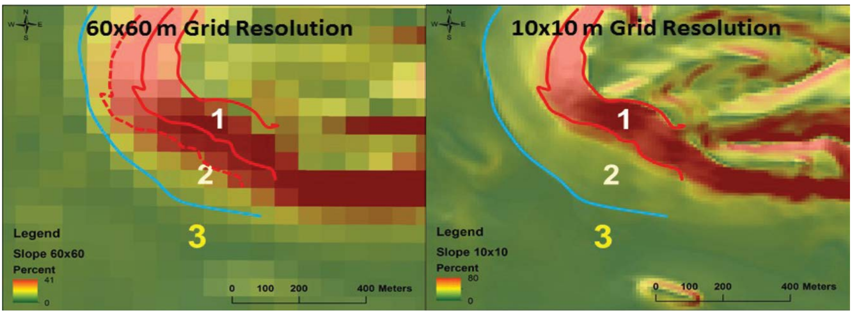


Diagram of the change in surface fragments along a transect of a scarp slope on a cuesta in Culbertson County, Texas. The progressive reduction in dominant size and percentage as one moves down slope demonstrates the impact of hillslope processes at a local level. On the upper backslope, dominant erosional hillslope processes are evidenced by the presence of flagstones on the surface. On the middle and lower backslopes, the percentages and sizes of surface fragments (channers and others) are indicative of lateral transport. On the lower footslope and toeslope, rock fragments are dominantly medium and fine gravel with decreasing percentages. They are indicative of deposition processes.

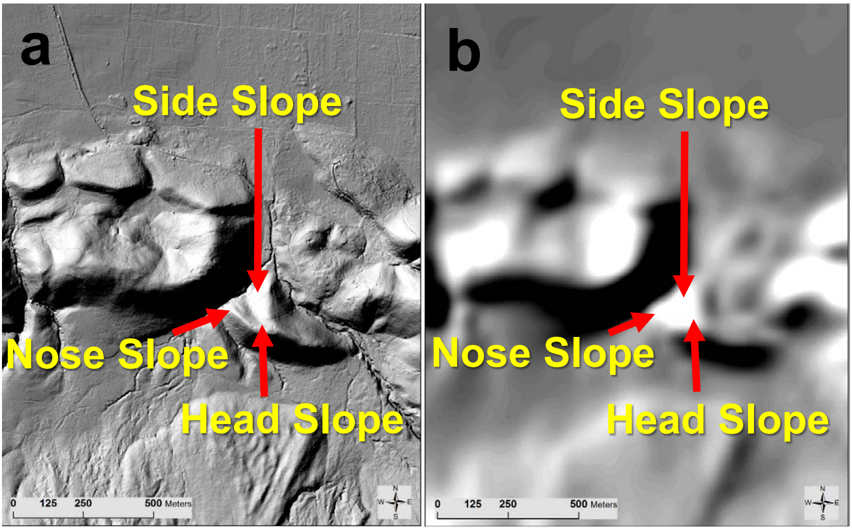
Figure 2-4



A comparison of digital maps with 60 x 60 m (left) and 10 x 10 m (right) grid sizes demonstrates the detail at different resolutions. The 60 x 60 m grid visually captures the three major landform units but not the geomorphic components of hills, namely nose slope, side slope, and head slope. An even finer resolution, such as LiDAR elevation data, is needed to capture the physical expressions of very localized hillslope processes.

In the digital environment, grid scales can be used to determine which resolution best captures important attributes for landscape modeling. What is apparent at one scale may not be apparent at another (fig. 2-4). Digital smoothing techniques, while appropriate for some analyses, can adversely affect the ability to identify features at a given scale (fig. 2-5).

Figure 2-5



Images showing changes in slope class interpretation as affected by digital elevation model (DEM) resolution from LiDAR. Image a—Grid size (1 x 1 m) captures surface features nested within hillslope position. Image b—As resolution decreases (30 x 30 m) and surface becomes digitally smoother, the geomorphic components of hills (nose, side, and head slopes) are no longer visible.

Placing Soil-Landscape Relationships in Their Proper Context

Soil geomorphology can be used effectively to evaluate, recognize, and communicate the context (setting) of natural systems. Context is key to:

1. Recognizing and understanding the materials and processes occurring at a given location or area.
2. Effectively predicting the distribution of materials that dominate the area. Commonly, the first and most useful question is "Where

are you on the planet?" (i.e., the geomorphic context rather than the geographic coordinates).

3. Recognizing the dynamic processes and relationships active between and within soils and land areas.

Development Stages for Soil-Landscape Models: Expectations vs. Reality

Developing accurate landscape models begins with using expert knowledge and experience to anticipate and portray relationships between landscapes, geomorphic systems, and soils. In whatever form, an initial model must be rigorously tested ("ground-truthed") and revised as needed to accurately reflect actual, observed relationships of soils and landscapes.

Developing Initial Soil-Landscape Models

It is helpful for scientists to have a general expectation of what they will encounter in an area or at a given site. For example, if the site is in a river valley, it is reasonable to expect that the site will reflect fluvial dynamics and features in the landforms, sediments, and soils of the area. The location of the site within the river valley (e.g., headwaters vs. delta) can further refine preliminary expectations. Headwater fluvial sediments, and the soils that formed in them, may be expected to contain more, larger, and less rounded coarse fragments, be somewhat less well sorted, and have less contrasting sediment strata than fluvial sediments in a delta. In addition, general conditions and dynamics for a water table might be anticipated (e.g., gaining stream vs. losing stream) based on the prevailing climate. A preliminary model can provide a tentative framework in which scientists can begin to efficiently investigate, understand, and give order to a diverse natural world. In the digital world, this now includes considerable pre-mapping, based primarily upon improved, detailed digital elevation models and existing information (see chapter 5). Preliminary soil-landscape models are helpful. The adage "If I hadn't known about it, I wouldn't have recognized it" is a relevant and practical truth. The more one understands a natural system, the easier it becomes to recognize the physical expressions of those systems.

Describing and Recording What is Actually There

Although soil-landscape models can be very useful at any stage of soil inventory, it is critical that a scientist maintain an open mind and adjust models as new information becomes available. A common error by field workers is to continue to defer to a preconceived expectation, such as a preliminary landscape model, rather than to adapt their ideas based on what is actually encountered. If a landscape model fails to match the natural features and sediments actually found, it must be modified or abandoned. A useful model should fit the facts, not the reverse.

Consistently Describing Landscapes, Landforms, and Geomorphology

There are various major kinds of information typically gathered to identify, evaluate, or communicate geomorphic information. A descriptive system and set of terms that can be used consistently are important for conveying the information accurately between individuals and making valid comparisons from place to place. The NCSS generally uses the Geomorphic Description System, or GDS (Schoeneberger and Wysocki, 2012). The system consists of three main sections:

Physiographic location.—A named geographic area is specified with a defined location.

Geomorphic description.—A discrete land surface feature (a separate entity) or an assemblage of features is identified. Features are categorized by dominant process of origin or geomorphic setting.

Surface morphometry.—Land surface shape or geometry is described. A discrete portion of a geomorphically defined land feature, area, or slope segment is identified. Microrelief, drainage patterns, and other surface features are also described.

Geographic and Physiographic Information

Geographic and physiographic information primarily addresses the question "Where is it?" It identifies the specific location of an area on the planet (e.g., the Appalachian Mountains). This information has powerful communication value to a wide range of people. Most people can relate a geographic name to some understanding of an area. Fewer users appreciate explicit technical descriptions (e.g., an eroded, folded, paleo-continental margin mountain system). The Appalachian Mountains and the Rocky Mountains are both mountain systems in the geomorphic sense, yet they differ in important geographic locations as well as geomorphic details. Their names emphasize geographic differences, not the geologic composition or type of mountains. Geographic and physiographic names may or may not accurately reflect the actual geomorphology. Confusion can arise if geographic names include geomorphic terms that do not adhere to their technical geomorphic meaning. For example, an area geographically identified as Thompson's Bench may geomorphically be something other than a true structural bench, such as a stream terrace or a horst.

Physiographic information combines geographic information with limited geomorphic information to describe location. In physiography, distinctions in topography, bedrock or parent material, watersheds, and other attributes are used to group geomorphically similar or related areas. Experience has consistently demonstrated that physiographic information is the most robust, versatile, and least ephemeral basis for describing and partitioning the landscape mosaic. Other location approaches emphasize spatial distinctions based on something other than physiography. For example, some approaches emphasize natural ecological environments or land management systems. The most appropriate descriptive framework for location is determined by the survey perspectives and goals.

Physiographic Location

Because there are numerous and diverse users of soil survey information, there are various perspectives and objectives. A single scale of information cannot best serve all of them. A homeowner has different needs and interests than a regional planner or a resource management government agency with national scope. Information on physiographic location can be usefully partitioned within a generalized hierarchy of scale (table 2-1). In the United States, the highest three levels are based on work by Fenneman (1957) for the conterminous U.S. and by Wahrhaftig (1965) for Alaska. Additional lower levels describe physiographic areas within States and more localized areas.

Table 2-1

Physiographic Location, Relative Scale (in Descending Order) and Examples in the U.S.

Physiographic location level	Relative scale	Example*
Physiographic division	Continental scale	Interior Plains
Physiographic province	Regional scale	Central Lowland
Physiographic section	Sub-regional scale	Wisconsin Driftless Section
State physiographic area	State scale	Wisconsin Dells
Local physiographic name	Local scale	Blackhawk Island

* Progressive levels of detail.

Maps are available for the three upper physiographic levels from Fenneman (1957). They are reproduced in the *Geomorphic Description System* (Schoeneberger and Wysocki, 2012). Maps of State physiographic areas are generally available through State Geological Survey offices or from the local university NCSS cooperators. Information on local physiographic names is primarily obtained from U.S. Geological Survey topographic quadrangle maps, where available.

Geomorphic Description

Geomorphic description attempts to answer the questions "What is it?" and "How did it occur?" for natural features and sediments. Earth surface features can be effectively arrayed in various ways for particular needs. Two ways that complement one another are: (1) master lists loosely stratified by scale into landscapes, landforms, and microfeatures, and (2) lists arrayed by geomorphic environment (fluvial, eolian, etc.).

Scale

Earth surface features can be partitioned into any number of scale ranges, but three general levels have proven consistently effective: landscapes, landforms, and microfeatures.

Landscapes, features at the coarsest scale, are collective groups or families of related landforms and typically cover large areas. Examples are a mountain range and canyonlands (fig. 2-6). They are most important to general or reconnaissance surveys (order 3 or 4, see chapter 4).

Figure 2-6

A canyonlands landscape in the San Rafael Swell, Utah.

Landforms are discrete, individual features that are related to one another within the context of the larger landscape and can be mapped at conventional mapping scales, such as order 2 (fig. 2-7). They are typically local in size, but some can be quite large. It is helpful to remember that natural and anthropogenic landforms and microfeatures can be expressed as the result primarily of removal, transport, or deposition. For example, blowouts and borrow pits are the result of removal, longshore bars and active dunes are the result of transport, and alluvial fans and dredge spoils are the result of deposition.

Figure 2-7

Loess hill and river valley landforms in western Iowa, along the Missouri River.

Microfeatures are discrete, individual, earth surface features that are readily identifiable on the ground but are too small or intricate to display or capture at conventional mapping scales. Examples are vernal pools and turf hummocks (fig. 2-8). Where present, these mini-landforms can have substantial impact on internal water flow, soil development, natural ecosystems, and land management.

There are many choices within each of these major categories, particularly landforms. The choices within each category are commonly arrayed as alphabetized master lists, which are particularly appropriate for databases. Because of the huge number of choices, it is helpful to use subsets for the three main categories, arranged by geomorphic environment or other groupings of commonality.

Figure 2-8

Turf hummock microfeatures in a wet meadow in Oregon.

Geomorphic Environment

A geomorphic environment is a natural setting dominated by a geomorphic process of formation and modification and the resultant behavioral dynamics. For example, a fluvial geomorphic environment consists of landforms and associated sediments created directly by, or in response to, channel water flow (fluvial processes). In such a setting, present-day environmental dynamics, such as ground-water and water table dynamics, are likely to be largely controlled by the fluvial system that formed the area's landscape. Table 2-2 lists the prominent geomorphic environments that are most relevant to soils in the United States and extensive elsewhere in the world.

Multiple Geomorphic Processes

Sites may have evidence of more than one geomorphic process. Typically, these processes are not equal. One process tends to dominate a given land area, and other processes, if present, have a minor presence and influence. It is important to recognize the most pervasive process and its products because they establish the primary landscape configuration and sediment composition. It is also important to recognize secondary processes and their sediments where they substantively affect soils. For

Table 2-2

Prominent Geomorphic Environments and Processes in the U.S. and Examples

Geomorphic environment or other setting	Dominant process or attributes	Examples * LS = Landscape LF = Landform Micro = Microfeature
Coastal marine & estuarine	Wave or tidal control; areas near shore, shallow submarine areas	LS: coastal plain LF: nearshore zone Micro: shoreline
Lacustrine	Related to inland water bodies	LS: lake plain LF: lakebed Micro: strandline
Fluvial	Concentrated channel flow	LS: river valley LF: stream terrace Micro: bar
Solution	Dissolution and subsurface drainage	LS: cockpit karst LF: sinkhole Micro: solution corridor
Eolian	Wind related (erosional and depositional)	LS: dune field LF: barchan dune Micro: slip face
Glacial	Directly related to glaciers (glaciofluvial, etc.)	LS: till plain LF: ground moraine Micro: tarn
Periglacial	Non-glacial, cold climate (modern or relict)	LS: thermokarst LF: patterned ground Micro: stripe
Mass movement	Gravity	LS: breaklands LF: landslide Micro: sag
Volcanic & hydrothermal	Volcanic and/or hydrothermal processes	LS: volcanic field LF: lava flow Micro: tumulus
Tectonic & structural	Regional and local tectonic processes or crustal movement	LS: mountain range LF: graben Micro: sand boil

Table 2-2.—continued		
Geomorphic environment or other setting	**Dominant process or attributes**	**Examples * LS = Landscape LF = Landform Micro = Microfeature**
Erosional	Dominated by hillslope and sheet-wash processes (non-concentrated channel flow)	LS: breaklands LF: pediment Micro: gully
Wetlands	Vegetated and/or shallow wet areas and wet soils	LS: Everglades LF: mangrove swamp Micro: vernal pool
Water bodies	Surface water features; primarily open water	LS: ocean LF: oxbow lake Micro: pond
Subaqueous features	Permanently submerged features that support plant life or adjacent areas	LS: lagoon LF: lagoon bottom Micro: shoal

* For complete choice lists, see *Geomorphic Description System* (Schoeneberger and Wysocki, 2012).

example, loess commonly mantles till plains in continental glaciated environments. If the loess cap is relatively thin, the dominant and most important geomorphic context is glacial because it explains the prevailing land features, topography, and unconsolidated materials. The loess should be recognized for what it is, and not some other geologic deposit, and correctly identified and described in the soil stratigraphy. If the loess cap is thick, it can supersede underlying glacial materials and function as the determinant geomorphic setting itself, such as loess hills. Although very thin (e.g., ≤ 25 cm) surficial sediments are prone to mixing by normal pedologic processes, to the point that they lose their identifying depositional morphology, they can still have an important influence on the soil. In this case, these materials may be identified even though their geomorphic process is not recognized overtly. Loess-influenced colluvium is an example.

Some geomorphic descriptive systems attempt to capture both primary and secondary geomorphic processes at a site. This approach, which may be appropriate for mapping geomorphology, can become complex and confusing when addressing soil geomorphology in the context of soil inventory. The main objective of soil inventory is to address the geomorphic processes and products that directly or substantively influence soils and soil behavior. Larger scale or deep-seated geomorphic processes that do not directly or substantively affect soils, such as deep-seated tectonic or structural phenomena, may be beyond the scope of soil inventory. This information can be included with the physiographic information or in general discussions.

Generic vs. Specific Geomorphic Terms

There is considerable range in the specificity of geomorphic terms. Some terms are very generic (e.g., uplands) and can be useful especially at the coarsest scales. While technically correct, generic terms convey relatively little information. Other terms are more specific (e.g., fault-block mountains). As a general rule, it is better to be more explicit than less. A specific term is more informative than an equally correct but more generic term. For example, "loess hill" provides more information than "hill."

Nested Features

The focus in geomorphic description is commonly the land feature (i.e., a single landform or a dominant landscape) that is most critical to soils and that conveys the most relevant context of that site or area. An example is "Alpha soil occurs on a dune." The foremost feature should be the one that most directly impacts or defines the soil. In some environments, there are multiple landforms of different scales that are each relevant to soil behavior and important in documenting an area. For these, multiple landforms can be used in sequence (nested) to convey important setting information. An example is "Alpha soil occurs on a dune on a stream terrace." If nested terms are used, typically no more than two or three are necessary.

Anthropogenic Features

Historically, soil survey in the United States has focused on natural processes, associated sediments, and resulting surface features, such as landscapes, landforms, and microfeatures. Human-altered surface features and materials were traditionally excluded or minimally recognized. They were considered to be artificial phenomena, unpredictable in composition and occurrence, and largely outside the scope of natural process-based soil survey. In recent years, however, there has been a growing awareness and acceptance of the impact of humans upon natural systems and associated features and materials. Anthropogenic features and materials differ from natural phenomena in their origin and processes of formation but can be surveyed in ways similar to those used for conventional geomorphic entities. For example, they can be identified by recurring surface expression (form and arrangement), range of composition and internal arrangement, and lateral extent. As with natural landforms and materials, the ability to consistently partition anthropogenic features into meaningful subsets facilitates recognition of anthropogenic soil geography and greatly assists in land management decisions that concern them.

Terms describing anthropogenic features were adopted by the NCSS in 1993. A new geomorphic category was established to accommodate human-altered or -created features of all scales and to elevate their recognition to the same stature as natural features (Schoeneberger and Wysocki, 2012). Since then, appreciation of the extent of human alterations of the Earth's surface has continued to evolve. As the number and variety of recognized anthropogenic features increased, proposals were made to divide anthropogenic features into three subsets loosely analogous to partitions of naturally derived earth surface features (Schoeneberger and Scheyer, 2005; Schoeneberger et al., 2012). Furthermore, the International Committee on Anthropogenic Soils (ICOMANTH, 2012) defined the phrase "anthropogenic feature" in a non-geomorphic context (any artificial artifact, mark, mold, impression, etc.). Subsequently, "anthropogenic features" (geomorphic context) has been replaced with three new, loosely scale-dependent categories: anthroscapes, anthropogenic landforms, and anthropogenic microfeatures.

An *anthroscape* is important both for its evocative simplicity as a term and its explicit recognition of human-modified lands as legitimate and significant areas. These lands are substantially different from natural systems because they have different sediments, arrangements of sediments, and water dynamics and subsequently require different management practices. An anthroscape is a human-modified "landscape" of substantial and permanent alterations formed by the removal, addition, or reorganization of the physical shape and/or internal stratigraphy of the land. It is associated with management for habitation, commerce, food or fiber production, recreation, and other human activities that have substantively altered water flow and sediment transport across or within the regolith. Types of anthroscapes include urban, suburban, reclaimed land, and agricultural.

An *anthropogenic landform* is a discrete, human-made "landform" on the Earth's surface or in shallow water that has an internal composition of unconsolidated earthy, organic, human-transported materials, or rock. It typically has straight line boundaries or geometric shape. It is the direct result of human manipulation or activities. It can be mapped at common soil survey scales, such as order 2 (> 1:10,000 to < 1:24,000). Anthropogenic landforms can originate from deposition (e.g., an artificial levee) or removal (e.g., a quarry; fig. 2-9).

Figure 2-9

Quarries are an example of an anthropogenic landform.

An *anthropogenic microfeature* is a discrete, individual, human-derived form on the Earth's surface or in shallow water that has a range in composition of unconsolidated earthy, organic, human-transported materials, or rock. It typically has a recognizable human-imposed shape. It is the direct result of human manipulation or activities. It typically cannot be mapped at common soil survey scales, such as order 1 (< 1:10,000) but can be observed locally. Anthropogenic microfeatures can originate from deposition (e.g., a conservation terrace; fig. 2-10) or removal (e.g., a ditch).

Ideas of anthropogenic features will continue to evolve and grow in coming years. The proposal to recognize a new geologic age—the Anthropocene—continues to gain support and reflects this overall trend. Information on composition, occurrence, and behavior of anthropogenic features and materials, despite their unique differences from "natural" geomorphic phenomena and processes, can assist in wise land management.

Figure 2-10

Soil conservation terraces are an example of an anthropogenic microfeature.

Surface Morphometry

Surface morphometry uses various terms to describe land surface shape or geometry, discrete portions of a geomorphic entity or slope segment, and miscellaneous features that are fundamental to soil and natural resource inventory. Several terms are discussed in the following paragraphs.

Elevation is the height of a point on the Earth's surface, relative to mean sea level. This information is widely available from common GIS databases and historically from topographic maps. Elevation conveys the important climatic context and reflects the relative potential and kinetic energy available at a location.

Soil slope has a scale connotation. It refers to the ground surface configuration for scales that exceed about 10 meters and range up to the landscape as a whole. It has gradient, complexity, length, and aspect. The scale of reference commonly exceeds that of the pedon and should be indicated. It may include an entire map unit delineation, a soil component within the map unit delineation, or an arbitrary area. Most commonly, slope is recorded in pedon descriptions for the segment of the landscape extending a few tens of meters above and below the site of the soil profile described and is representative for the landscape segment occupied by the soil component at that site.

Slope aspect is the compass bearing that a slope faces looking down slope. It is recorded either in degrees, accounting for declination, or as a general compass orientation. The direction is expressed as an angle between 0 and 360 degrees (measured clockwise from true north) or as a compass point, such as east or north-northwest.

Aspect can substantially impact local ecosystems. The impact generally increases as slope gradient and latitude increase. In the mid latitudes of the conterminous United States, this effect becomes particularly important on slopes of approximately 6 to 8 percent or greater. Increased or decreased solar radiation on slopes due to aspect can affect water dynamics across a site (fig. 2-11). In the northern hemisphere, north-northeast aspects reduce evapotranspiration and result in greater soil moisture levels, improved plant growth and biomass production, higher carbon levels, and improved drought survival rates for plants. Increased solar radiation on south-southwest aspects increases evapotranspiration and decreases biomass production, seedling survival rates, and drought survival rates for plants.

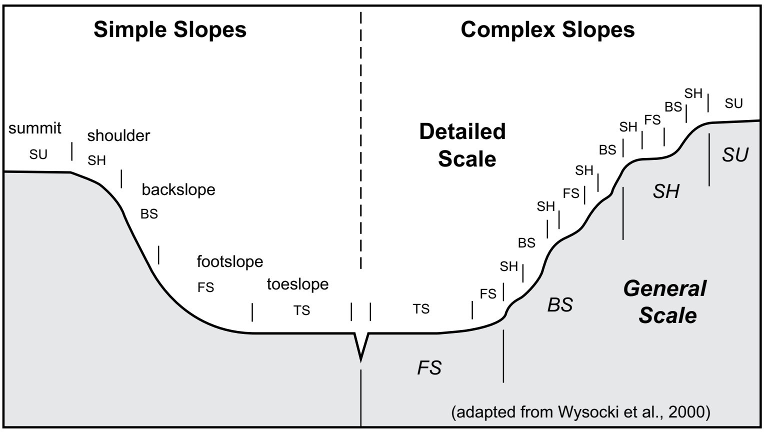
Figure 2-11

Effect of slope aspect on vegetation and tree seedling survival. (Photo courtesy of Kerry Arroues)

Slope gradient is the inclination of the land surface with respect to the horizontal plane. It is also commonly referred to as "slope percent" or simply "slope." It is calculated as the vertical distance divided by the horizontal distance ("rise over run"), multiplied by 100, determined at a point along a line oriented up and down slope. It directly controls the kinetic energy, erosive power, and sediment carrying capacity of running water (as overland flow or channel flow), all of which increase with increasing gradient. It inversely affects the amount of time that internal soil water is present. Many soil conservation practices, such as conservation terraces, are designed primarily to reduce slope gradient to minimize soil erosion and increase infiltration. Slope gradient also directly affects land management practices by limiting ranges of operation for various types of equipment, such as tractors and log skidders.

Slope complexity is the relative linearity or smoothness (simple) or irregularity (complex) of the ground surface leading down slope and through the point or map unit of interest (fig. 2-12). Simple slopes allow the maximum slope length with comparatively unimpeded slope wash processes. In contrast, complex slopes are composed of a series of steps commonly associated with bedrock-controlled benches or other stepped surfaces (fig. 2-13). These localized breaks in slope reduce slope length, alter slope wash processes, and commonly correspond to changes in soil types.

Figure 2-12



Simple versus complex slopes and slope positions. Note the choice of a detailed or general scale approach to slope position for complex slopes (right side).

In many places, internal soil properties are more closely related to the slope complexity than to the gradient. Slope complexity has an important influence on the amount and rate of runoff and on sedimentation associated with runoff. It can also affect soil temperature through local variation in soil aspect.

Traditionally, slope (gradient) classes are assigned to soil map units to convey the dominant range of slope gradients occurring within it. The numerical slope class limits of map units are not always consistent within or between survey areas. They can vary from one survey area to another, to better capture the local survey slope conditions, as long as they

Figure 2-13

Complex slopes on a hillslope of interbedded sedimentary rocks in Wildcat Hills, Nebraska.

generally remain within the maximum (upper) and minimum (lower) class limits (table 2-3). Descriptive adjectives corresponding to specified slope ranges can be used in text. Such adjectives are slightly different for the mid-range slope classes, depending upon whether the dominant slopes are simple or complex (table 2-3). Gently sloping or undulating soil map units, for example, can be defined with slope class ranges as broad as 1 to 8 percent or as narrow as 3 to 5 percent. Classes may exceed the broadest range indicated in table 2-3 by one or two percentage points where the range is narrow and by as much as 5 percent or more where the range is broad. The slope class terms can also be used in naming slope phases of map units, as discussed in chapter 4.

If the detail of mapping requires slope classes that are more detailed than those in table 2-3, some or all of the slope classes can be subdivided as follows:

Nearly level.—Level, nearly level
Gently sloping.—Very gently sloping, gently sloping
Strongly sloping.—Sloping, strongly sloping, moderately sloping
Undulating.—Gently undulating, undulating
Rolling.—Rolling, strongly rolling

Table 2-3

Definitions of Slope Classes

Classes for—		Recommended slope (gradient) class limits	
Simple slopes	Complex slopes	Lower (percent)	Upper (percent)
Nearly level	Nearly level	0	3
Gently sloping	Undulating	1	8
Strongly sloping	Rolling	4	16
Moderately steep	Hilly	10	30
Steep	Steep	20	60
Very steep	Very steep	> 45	

In a highly detailed survey, for example, slope classes of 0 to 1 percent and 1 to 3 percent would be named "level" and "nearly level," respectively.

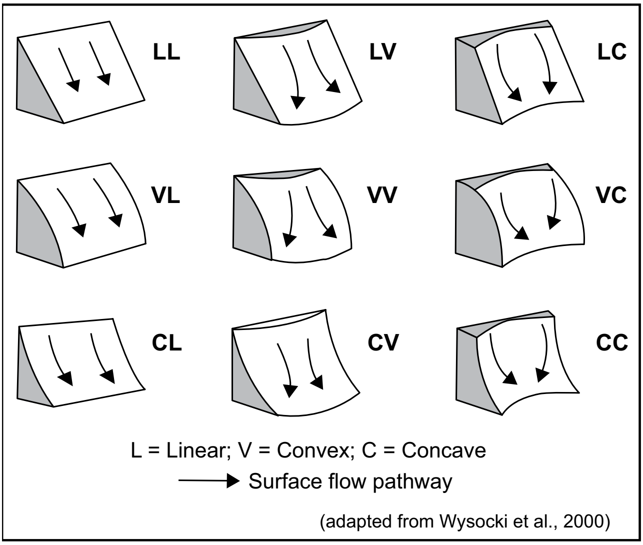
Slope length is rarely used directly in soil mapping because its range across all the polygons of a soil map unit is highly variable. Furthermore, natural slope lengths are commonly interrupted and artificially shortened by human-made features such as ditches, roads, or field boundaries. Slope length does have important uses in key soil erosion programs and models, including the Revised Universal Soil Loss Equation, version 2 (USDA-NRCS, 2016d). It has considerable control over surface water runoff and potential for accelerated water erosion. Generic terms such as "long" or "short" can be used to describe slope lengths that are typical of certain kinds of soils. These terms are typically relative within a physiographic region. A "long" slope in one place might be considered "short" in another. If such terms are used, they are defined locally. For observations at a particular point, it may be useful to record the length of the slope that contributes water to that point (called *point runoff slope length*) as well as the total length of the slope. The *sediment transport slope length* is the distance from the expected or observed initiation point upslope of runoff to the highest local elevation where deposition of sediment is expected to occur. This distance is not necessarily the same as the point runoff slope length.

Relative slope segment position indicates vertical subdivisions of long slopes. It can be useful, especially in areas of substantial slope length, to identify general "slope segment" positions, such as lower third, middle third, and upper third. For example, the long slopes of mountainflanks commonly exhibit changes in bedrock stratigraphy somewhere along the slope that correspond to soil types that differ in parent material composition and type and amount of rock fragments.

Slope shape is the dominant form of the ground surface curvature. It is expressed in two directions, which are paired (fig. 2-14): up and down slope (vertical, or perpendicular or normal to the slope contour) and across slope (horizontal, or along the slope contour). When used in tandem, the slope directions describe the configuration of the surface of a portion of the slope and the soil upon it. Both slope directions can be described by one of three curvature shapes: convex, linear, or concave. In the up and down direction, the surface of a linear slope is substantially a straight line when seen in profile at right angles to the contours. The gradient neither increases nor decreases significantly with distance (fig. 2-14, top row). An example is the dip slope of a cuesta. On a concave slope (fig. 2-14, bottom row), gradient decreases down the slope. An example is a footslope. Where the slope decreases, runoff water decelerates and tends to deposit sediments, as on the lower parts of the hillslope. Simultaneously, as surface water flow slows, it has greater opportunity to infiltrate into the soil. On a convex slope, such as the shoulder of a hill or ridge, gradient increases down the slope and runoff tends to accelerate as it flows down (fig. 2-15, middle row). If contours are substantially straight lines (parallel), as on the side of a lateral moraine, the across slope shape is linear. An alluvial fan has a convex contour that bows outward. A cirque has concave contours. In figure 2-15, nine possible combinations of linear (L), concave (C), and convex (V) slopes are shown. For both the up and down orientation and the across slope orientation, where the slope is convex (fig. 2-14, middle column), surface runoff water tends to diverge (spread apart) as it moves down the slope. As a result, overland flow is dissipated and both the erosive power and the amount of water available for infiltration are reduced. Where the slope is concave, surface runoff water tends to converge, or concentrate (fig. 2-14, right column). The most intense concentration of running water occurs where both orientations are concave, as in a swale on a hillside or in a head slope at the head of a drainageway (fig. 2-15). The most intense divergence of running water occurs where both orientations are convex, as on a nose slope at the end of a ridge (fig. 2-15).

Hillslope profile positions (also called *hillslope positions*) refer to two-dimensional segments of a line used to describe slope position along a transect oriented up and down slope (normal to the slope contour). They do not address lateral dimensions. These line segments, progressing from the top of the slope to the bottom, are: summit, shoulder, backslope,

Figure 2-14



Slope shape based on combinations (up and down slope and across slope) of surface curvature.

footslope, and toeslope (see fig. 2-12). These terms have proven useful for many decades because they can describe areas on slopes where soil bodies are consistent and breaks in slope curvature where soils typically change. They can be used alone or in a combination to verbally capture where soils recur up and down slopes.

Geomorphic components are similar to hillslope profile positions (up and down slope) but include an additional lateral dimension (across slope) that enables distinctions to be made between the slope curvatures of land areas in three dimensions. They indicate patterns of surface water flow, such as concentration, dispersion, or parallel (lateral) flow. Not all settings, however, share the same, recurrent configurations. For this reason, geomorphic component descriptors have been developed for four different settings: hills, terraces and stepped landforms, mountains, and flat plains (tables 2-4 to 2-7 and figs. 2-15 to 2-18).

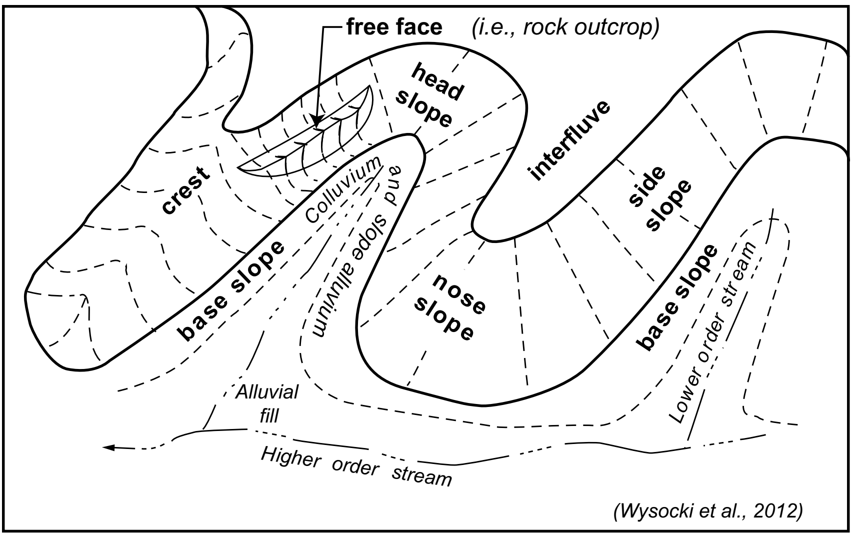
As with hillslope profile positions, geomorphic components for hills have been widely used in one form or another. These terms and concepts work very well for partitioning and describing hilly terrain as functionally distinct members. However, these same concepts work poorly when applied to very gentle terrain. The kinetic energy of running water is dramatically and functionally less at low gradients. The erosive

Table 2-4

Geomorphic Component Terms for Hills

Geomorphic component term	Typical attributes
Interfluve	High, relatively level area that generally does not receive run-on surface flow; residuum, short-transport colluvium
Crest	High, narrow area; converging backwearing slopes that form a lowered ridge
Head slope	Convergent overland water flow; thickened colluvium, slope alluvium
Side slope	Parallel overland waterflow; colluvium, slope alluvium, pedisediment, residuum
Nose slope	Divergent overland water flow; colluvium, slope alluvium, pedisediment
Free face	Rock outcrop
Base slope	Concave surface; colluvium, slope alluvium

Figure 2-15



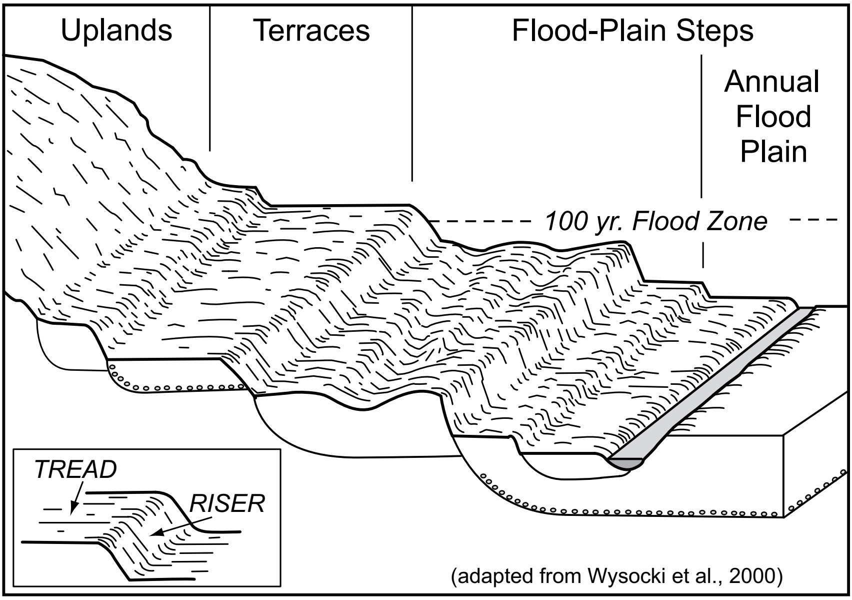
Three-dimensional depiction of geomorphic components of hills.

Table 2-5

Geomorphic Component Terms for Terraces and Stepped Landforms

Geomorphic component term	Typical attributes
Tread	Relatively level, broad surface
Riser	Vertical or steep side slope separating treads

Figure 2-16



Three-dimensional depiction of geomorphic components of terraces and stepped landforms.

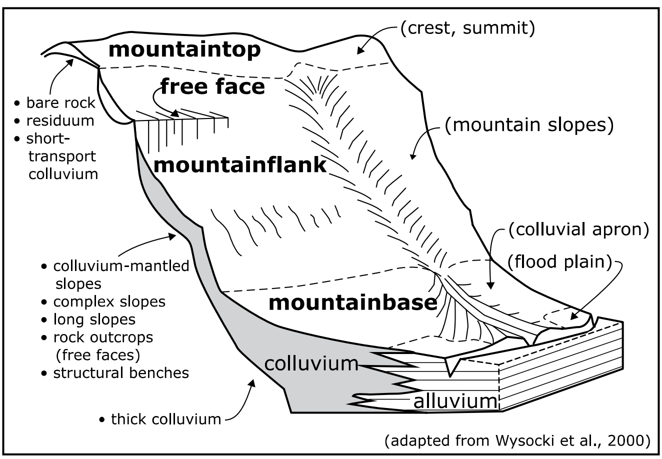
power of the water is reduced as well as its sediment carrying capacity, which determines what sediments are removed and which are left behind. Additionally, there is a general increase, compared to higher gradient systems, in the residence time of water, particularly internal soil water, which alters the biogeochemical dynamics and products. Therefore, new concepts and associated terms were developed for geomorphic components of flat plains. In a similar way, hillslope components were found to be inadequate when applied to high-gradient terrain. Very long and commonly complex slopes and much greater kinetic energy dramatically increase erosion potential and the sediment carrying capacity, can change sediment winnowing effects, can decrease soil water residence time, and can otherwise alter system dynamics and resulting sediments and soils. Therefore, new concepts and associated terms were developed for geomorphic components of mountains. Stream terrace and stepped landforms are also sufficiently unique to warrant separate geomorphic component descriptors.

Table 2-6

Geomorphic Component Terms for Mountains

Geomorphic component term	Typical attributes
Mountaintop	High area (crest, summit); residuum or short transport colluvium, solifluction deposits; generally does not receive run-on surface flow
Mountainflank	Complex slopes, long slopes, substantial gradients, colluvium, mass wasting deposits, talus
Free face	Rock outcrop
Mountainbase	Concave surface; thick colluvium, slope alluvium, mass wasting deposits

Figure 2-17



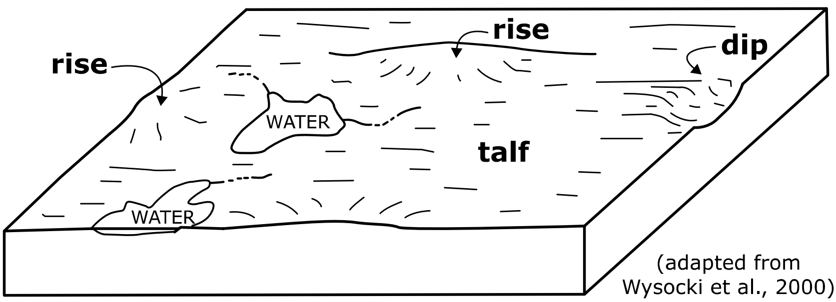
Three-dimensional depiction of geomorphic components of mountains.

Table 2-7

Geomorphic Component Terms for Flat Plains

Geomorphic component term	Typical attributes
Rise	Slightly elevated area (1-3% slopes)
Talf	Very low slope gradients (0-1%); deranged or incipient drainage network; lacustrine deposits, alluvium, till, marine deposits, eolian deposits, and other flat-lying deposits
Dip	Depressions; backswamp deposits, marl, organic deposits, and other deposits in low-lying areas

Figure 2-18

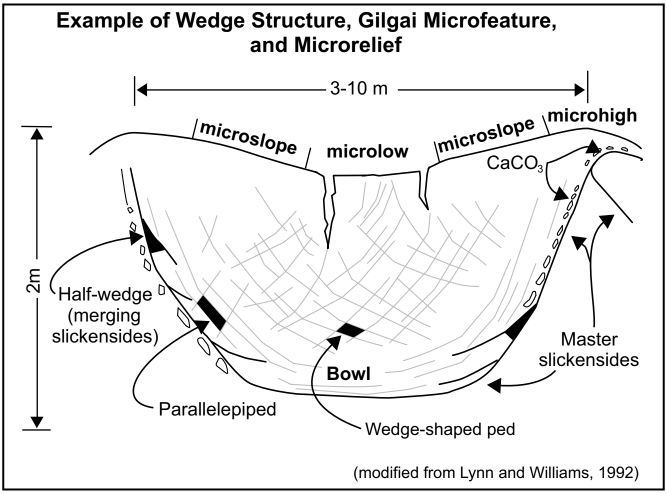


- very low gradients (e.g., slope 0-1%)
- deranged, nonintegrated, or incipient drainage network
- “high areas” are broad and low (e.g., slope 1-3%)
- sediments, commonly lacustrine, alluvial, eolian, or till

Three-dimensional depiction of geomorphic components of flat plains.

Microrelief refers generically to small, relative elevational differences between adjacent areas on the earth surface. In subaerial settings, minor elevational differences can profoundly influence plant growth above ground and, subsequently, water conditions below ground. The lateral scale across which the elevational differences occur is generally on the order of about 3 to 10 meters but can be smaller. A gilgai, which has micro site differences in patterned ground, is an example (fig. 2-19). Terms used to describe microrelief positions are microhigh, microslope, and microlow.

Figure 2-19



Water ponds in the microlows in this area of Vertisols that exhibits gilgai microfeatures (mounds and bowls).

Drainage patterns (also called a *drainage network*) describe the recurring arrangement of interconnected drainage channels across the surface of a land area. They provide substantial insight into the underground, controlling bedrock or regolith (see Way, 1973) as well as the locations where these materials and the overlying soils change. Figure 2-20 presents the more general patterns. Drainage patterns can be best observed and evaluated on aerial photographs, topographic quadrangle maps, or GIS spatial layers that present drainageway patterns in detail.

Figure 2-20

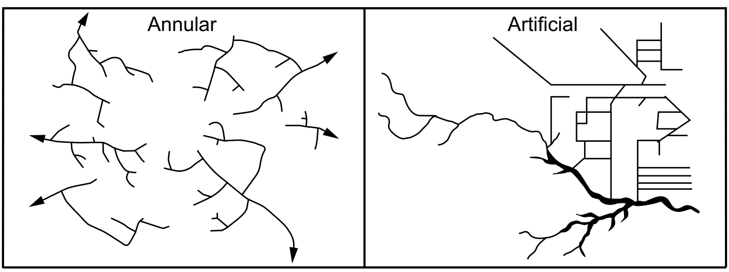


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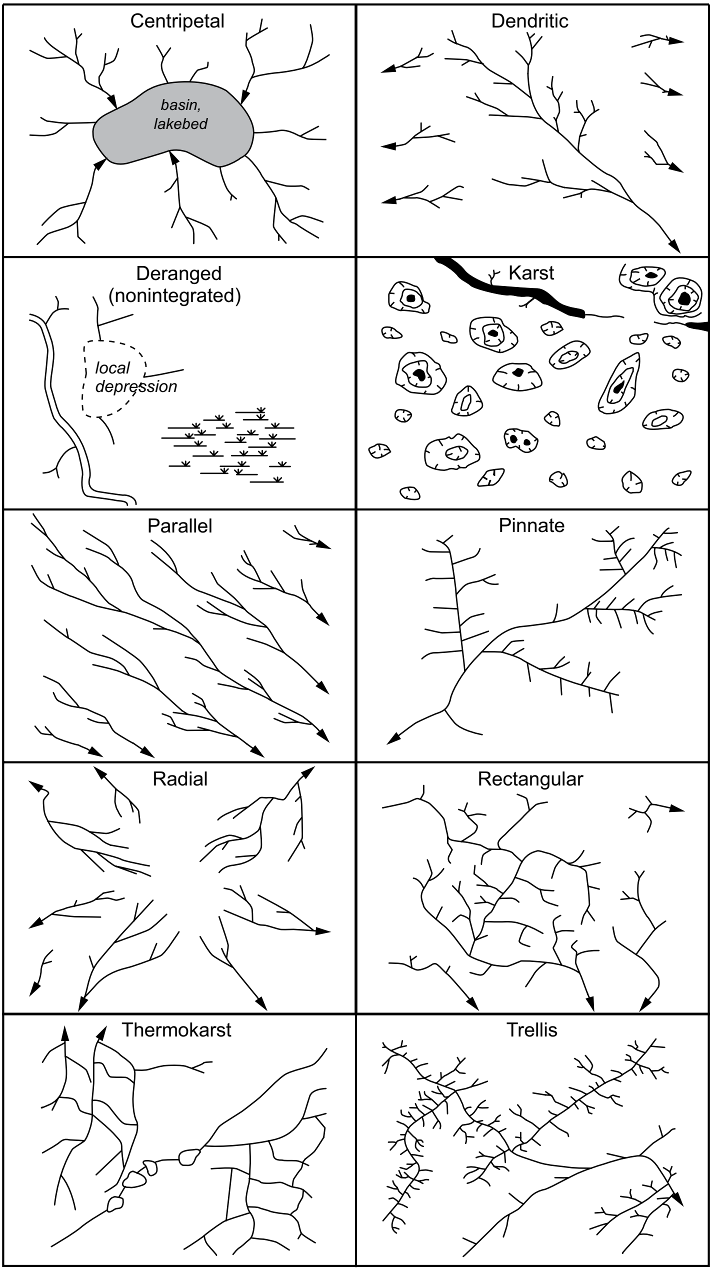
Figure 2-20.—continued



Illustrations and descriptive terms for drainage patterns.

Parent Material

Soil parent material refers to the unconsolidated, organic and mineral materials in which soils form. The unconsolidated material, or regolith, in which a soil develops exerts tremendous influence upon what that soil is and is not and how it behaves. Determining the parent material is therefore important in accurately identifying the composition of the soil. Parent material is more than just soil texture. Other attributes, such as mineralogy, stratigraphy, and the degree of sorting and particle rounding, can substantially affect soil behavior. Eolian sand, such as dunes, can behave hydrologically different than beach sand deposits, even though both are made of sand, due to differences in the internal arrangement and lateral continuity of primary particles. Accurate identification conveys direct and implicit information about the soil itself, the environment in which it formed, and its current environment. Soils provide a record of prevailing and past environments, climates, human activities, and much more.

Importance of Parent Material in Understanding the Soil

Soil formation involves alterations, such as additions, losses, transformations, and translocations and including weathering, of unconsolidated earthy or organic materials (Simonson, 1959). The parent material of a genetic soil horizon cannot be observed in its original state as it has undergone soil formation. Rather, the original state must be inferred from the properties that the horizon has inherited and from other evidence, such as the geomorphic context. In some soils, the parent material has changed little and what it was originally can be deduced with confidence. In other soils, such as some very old, highly altered soils of the Tropics, the specific kind of parent material or its mode of deposition is less clear and more speculative. Regardless, the influence that parent material exerts on the inherent properties and subsequent behavior of soil is substantial. Parent material determines the broad characteristics of what is geochemically present or absent. It directly affects the physical architecture that makes up a soil.

Much of the mineral matter in which soils form is derived from hard bedrock in some way. Glaciers may grind the bedrock into fragments and smaller particles and deposit the unsorted mixture as till. Wind and running water can abrade and entrain small particles that accumulate elsewhere as eolian or fluvial deposits. Bedrock may be weathered and significantly changed chemically and physically but not be moved from its place of origin. Little may be gained from attempting to differentiate between geologic weathering and soil formation because both are weathering processes. It may be possible to infer that a material was weathered before soil formation. The weathering process causes some bedrock constituents to be lost, some to be transformed, and others to be concentrated.

Soil parent material is not always residuum weathered directly from underlying bedrock. The material that developed into the modern soil may not be related to the underlying bedrock at all. In fact, most soils did not form in place but were subject to transport and deposition by wind, water, gravity, or human activities.

Seldom is there absolute certainty that a highly weathered material actually weathered in place. The term "residuum" is used if the properties of the soil indicate that it has been derived from rock similar to that which underlies it and if there is no overt evidence that it has been modified by movement. A decrease in the amount of rock fragments as depth increases, especially over saprolite, indicates that soil material probably has been transported down slope. Stone lines, especially if the stones have a different lithology than the underlying bedrock, are evidence that the soil did not form entirely in residuum. In some soils, transported material overlies residuum and illuvial organic matter and clay are superimposed across the discontinuity between the contrasting materials. A certain degree of landscape stability is inferred for soils that formed in residuum. A lesser degree is inferred for soils that developed in transported material.

Standard terms are used to describe both consolidated and unconsolidated materials beneath the solum that influence the genesis and behavior of the soil. Besides primary observations, the scientist uses his own judgement to infer the origin of the parent material from which the solum developed. Primary observations must precede, and be clearly separated from, inferences.

The lithologic composition, structure, and consistence of the material directly beneath the solum are important. Evidence of stratification of the material should be noted. It includes textural differences, stone lines, and changes in kind and amount of coarse fragments. Commonly, the upper layers of outwash deposits settled out of more slowly moving water and are finer in texture than the lower layers. Windblown material and volcanic ash are laid down at different rates in blankets of varying thickness. Examples of such complexities are nearly endless.

Where alluvium, eolian sands, volcanic ash, or colluvium is rapidly deposited on old soils, buried soils may be well preserved. In other places, the accumulation is so slow that the thicknes of the solum increases only gradually. In these places, the material beneath the solum that was once near the surface may now be buried below the zone of active change.

Where hard rocks or other strongly contrasting materials lie close enough to the surface to affect soil behavior, their properties and the depth to contact need to be measured accurately. The depth of soil over such nonconforming materials is an important criterion for distinguishing different kinds of soil.

General Kinds of Parent Materials

Broad groupings of parent material are discussed in the following paragraphs. Consistent use of terminology to describe parent materials in pedon descriptions and databases enhances the usefulness of the information and allows easier and more reliable comparison of soils that formed in the same kind of parent material. The NCSS has adopted standard terms for many kinds of parent material. These terms are presented in the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2012). The terms are fully defined in the *Glossary of Landforms and Geologic Terms* (USDA-NRCS, 2016b).

Material Produced by Weathering of Bedrock

The nature of the original rock affects the residual material produced by weathering. Bedrock undergoes various changes as it weathers, beginning with the progressive removal of readily weatherable minerals, such as plagioclase feldspar and biotite mica. The relative ease of weathering of major minerals was described by Goldich (1938) and refined for some soil clay minerals by McClelland (1950). This weathering sequence indicates which minerals weather most readily and the relative order in which weathering progresses. Evaluating which minerals are present and which have been removed can indicate the degree of weathering that rock has undergone (Coleman and Dethier, 1986).

In-place deposits.—*Saprolite* is soft, friable material produced by bedrock that has been highly weathered in place (*in situ*). The weathering process has removed mineral constituents but left the fabric and structure of the original rock without significant loss in volume (Pavitch, 1986). If the altered material has lost most or all rock fabric and structure and its original volume has been reduced (e.g., by void collapse), the unconsolidated, in-place earthy material is called *residuum*. Such distinctions are useful in recognizing close geochemical and physical relationships to the bedrock of origin. It is assumed that residuum is *in situ* and has not undergone substantive lateral displacement or transport.

Residuum is a major kind of parent material, particularly on older, stable landscapes and in warm and humid climates.

If the soil is derived directly from underlying bedrock and exhibits little or no evidence of lateral transport, the parent material should be identified (e.g., residuum, grus, saprolite, bauxite) and then paired with the kind of bedrock from which it was derived (see "Bedrock" section). The point where rock weathering ends and soil formation begins is not always clear. The processes may be consecutive or overlapping. Quite different soils may form from similar or identical rocks under different weathering conditions. Texture, color, consistence, and other characteristics of the parent material should be included in the description of soils, as well as important remnant bedrock features, such as quartz dikes. Information about the mineralogical composition, consistence, and structure of the parent rock is useful and should also be included.

Transported Material

Most soil parent materials have been moved from their place of origin and deposited elsewhere. The principal subsets of transported materials are typically arranged according to the main geomorphic process responsible for their transport and deposition. In most places, there is sufficient evidence to make a clear determination.

In soil morphology and classification, it is very important to observe and describe the characteristics of the parent material. It is not enough simply to identify the material. Any doubt regarding the identification should be mentioned. For example, it can be difficult to determine if silty deposits are alluvium or loess or to distinguish silty colluvium from silty residuum. It can also be difficult to distinguish certain mud flow deposits from till or to distinguish some sandy tills from sandy outwash. Additional observations across large exposures or at multiple locations help in making such distinctions. These distinctions provide supporting information needed to accurately inventory soils and thereby improve the accurate prediction of soil behavior.

Water-laid or water-transported deposits.—*Alluvium* is a widely occurring parent material. It consists of unconsolidated, sorted, clastic sediment deposited by running water, particularly channel flow. It may occur on actively flooded portions of modern streams. Remnants of old stream terraces may occur in dissected areas far away from, or high above, a present stream or occur as paleoterraces that are unrelated to the modern stream. In larger streams and rivers, a series of alluvial deposits in the form of stream terraces may loosely parallel the modern stream. The youngest deposits occur in the stream; deposits increase in age as they progress to higher levels. In some areas, recent alluvium covers older terraces. For example, younger alluvial fan sediments onlap and bury older fan sediments. Alluvium is also the dominant parent material in large tectonic valleys, such as the bolsons and semi-bolsons of the Basin and Range Physiographic Province in the western United States. On these broad, sloping landscapes, alluvium occurs as thick deposits on active alluvial fans and fan remnants or as broad, relatively level alluvial flats on basin floors. The further down a river system alluvium occurs, the better sorted the sediments tend to be. Larger stream systems commonly have backswamp deposits along low-gradient stream reaches. These lower energy areas are set back from the main channel and are dominated by sediments that are laminated and finer (silts and clays) than alluvium closer to the stream channel. Slope alluvium refers to hillslope sediments transported primarily by slope wash processes (sheet flow) rather than by the channel flow of streams. Crude lateral particle sorting is evident on long slopes, but it is much less evident than the particle sorting in alluvium derived from channel flow.

Lacustrine deposits consist of clastic sediments and chemical precipitates that settled out of bodies of still water, such as ponds and lakes. Deposits associated directly with glaciers and laid down in freshwater lakes (glaciolacustrine deposits) or in oceans (glaciomarine deposits) are included with other glacial deposits. Numerous basins in the western U.S. contained moderate to large pluvial lakes during the Pleistocene epoch. These lakes have either drastically shrunk or disappeared during the warmer and drier climates of the Holocene epoch. The now dry lakebeds are known as playas or salt flats and contain thick lacustrine deposits dominated by silt and clay with interbedded layers of volcanic ash. Some also contain substantial evaporate deposits. Soils in the narrow margins of these barren playas are generally saline, depending on climate and drainage, and are sparsely vegetated with salt-tolerant plants.

Marine deposits settled out of the sea, lagoons, or estuaries and commonly were reworked by currents and tides. Subaqueous soils include sediments that remain under water. Some marine deposits were later exposed either naturally by falling sea levels or following the construction of dikes and drainage canals. Many of the soils of the Atlantic and Gulf of Mexico Coastal Plains in the southeastern U.S. formed in marine sediments deposited during a time of higher sea level. These deposits vary widely in composition. In low-energy settings, such as lagoons, sediments tend to be finer textured and may have intermittent or substantial amounts of organic materials. Higher energy settings can have substantial amounts of sandy material (such as in areas of inlets and barrier islands) or coarser rock fragments (such as in areas of rocky coasts and headlands).

Beach deposits mark the present or former shorelines of lakes or oceans. They consist of low sheets or ridges of sorted material. They are commonly sandy or gravelly (along non-rocky coasts) or cobbly or stony (especially along rocky coasts).

Eolian deposits.—Eolian deposits are very well sorted windblown material. They are broadly divided into groups based on dominant particle size or origin. Examples are aerosols, dust, loess, and eolian sands. All but the finest wind-driven sediments share some depositional traits. "Lateral fining" refers to the progressive reduction in average particle size and deposit thickness as distance increases along the prevailing wind direction and away from the source area. The closer to an eolian sediment source (e.g., a large barren flood plain), the coarser the average particle size and the thicker the eolian deposit. The dominant particle sizes of discrete eolian deposits range from silt and very fine sands (loess) and from fine to medium sands (eolian sands).

Eolian sands are significant due to their physical prominence and the wide range of distinct landforms (especially dune types) they produce. Very fine and fine eolian sands commonly occur as dunes (Bagnold, 1941), and medium sands tend to form sand sheets. Eolian sands are common in, but not limited to, warm, dry regions. They characteristically consist of sands with a high content of quartz and a low content of clay-forming materials. Sand dunes may contain large amounts of calcium carbonate or gypsum, especially in deserts and semi-deserts.

During periods of drought and in deserts, local wind movements may mix and pile up soil materials of different grain sizes, including materials with a high content of clay. Sand-sized aggregates of clay (e.g., parna) can even form dunes (parna dunes). In areas where sand and finer eolian materials are intimately intermingled, the eolian materials may be identified generically as eolian deposits rather than as distinct loess or eolian sands.

Loess deposits are important because their physical and mineralogical properties make them highly suitable to food and fiber production worldwide. Their texture is typically very silty but may range from fine silt to very fine sand. Most loess is pale brown to brown, although gray and red colors are also common. Some colors are inherited from the source material (geogenic colors). Other colors, particularly gray colors, may be caused by post-deposition soil formation, such as redoximorphic alteration resulting in iron reduction. Although thick loess deposits appear to be relatively massive, they have some gross vertical cracking with coarse polygonal structure and can support nearly vertical walls (e.g., roadcut walls) for many years. Silty deposits that formed in other ways have some or all of these characteristics. Windblown silt that has been leached and strongly weathered can be acidic and rich in clay, whereas some young deposits of loess that are mainly silt and very fine sand have a low content of clay.

Other, finer windborne particles also affect soils in unique ways but are not generally recognized as a kind of parent material. Dust is composed of clay or very fine silt-sized particles and can be deposited dry or in precipitation. It can travel great distances from its point of origin, even circle the Earth in the upper atmosphere and be deposited in small increments across the world. After dust settles, the very fine particles are readily mixed into pre-existing soils and may substantially affect soil properties. However, they typically do not form readily identifiable, discrete deposits by themselves. Aerosols are the finest of particulate materials, so small that they can stay suspended in air for extended periods. Wood ash is an example. These particles are typically too fine and too diffuse to accumulate as separate deposits. Consequently, they are not identified as discrete parent materials in soil survey. Nonetheless, they can contribute meaningful amounts of carbon ash, pollen, quartz, or other materials to soils. They typically settle out as raindrop nuclei and infiltrate soil in suspension or settle in water bodies. Other soil constituents accompany precipitation, such as atmospheric elements in solution (fixed nitrogen, sulfur, calcium, magnesium, sodium, potassium, etc.) but are not included within the concept of parent materials.

A conventional practice in considering geomorphic processes is to include volcanic eolian deposits, such as ash and pumice, with other volcanic materials (see "Volcanic Deposits" below) because their origin, including mineralogical composition and depositional dynamics, is closely associated with volcanism.

Glacial and periglacial deposits.—Glacial and periglacial deposits are derived from material moved and deposited by glacial processes or associated with cold climates. However, the two types have two distinct geomorphic process systems. Their processes and sediments are commonly associated because they share very cold climatic settings and driving forces. They are considered together here for convenience. Glacial refers to materials that have been directly created, moved, and deposited by glacial ice (i.e., drift and till). A conventional practice in considering geomorphic processes is to include glaciofluvial, outwash, and glaciolacustrine deposits among other glacial materials because their origins, including depositional dynamics, resulting stratigraphy, and mineralogical composition, are closely associated.

Drift is a general, inclusive term for all material picked up, mixed, disintegrated, transported, and deposited by glacial ice or glacial meltwaters. The term is so generic that it is principally used for very coarse scales that prohibit details. In many places, drift is mantled by loess. Thick mantles of loess are typically easily recognized, but very thin mantles may be so mixed by soil-building processes that they can scarcely be differentiated from the underlying drift.

Till is a type of drift that was deposited directly by ice and had little or no transportation by water. It is generally an unstratified and heterogeneous (i.e., unsorted) mixture of clay, silt, sand, gravel, and boulders. Some of the ice-entrained mixture settled out as the ice melted and was subject to very little washing or reworking by water (ablation till), and some was overridden by the glacier and became compacted (lodgement till). Till occurs in various glacial landforms. Ground moraines and recessional moraines are examples. In many places, it is important to differentiate tills of several glaciations. Commonly, the tills underlie one another and may be separated by other deposits or old, weathered surfaces. In many cases, till was later eroded by the wave action in glacial lakes. The upper part of such wave-cut till may have a high percentage of rock fragments.

Till ranges widely in texture, chemical composition, and degree of weathering. It is principally affected by the composition of the bedrock it has overridden and whose materials it has entrained. Tills of the mid-continental U.S. are underlain by sedimentary rocks, such as limestone and shale, and typified by heavy textures (clay, clay loams). In contrast, tills of northern Minnesota, New England, and Canada underlain by crystalline bedrock, such as granite, are typified by coarser textures (gravelly sandy loam). Much till is calcareous, but a significant amount is noncalcareous because no carbonate rocks contributed to the till or because subsequent leaching and chemical weathering have removed the carbonates. The two most widely occurring and operationally important types of till are ablation till and lodgement till. Ablation till is characterized by a comparatively low bulk density (e.g., 1.4 g/cm^3) and occurs at the top of till deposits. Lodgement till formed beneath a glacier and was over-compacted. As a result, it has a very high bulk density (e.g., 1.8 g/cm^3) that substantially restricts internal water flow and makes excavation difficult. Some tills are identified by position of formation relative to the glacial ice. Supraglacial till formed by the sediments on top of or entrained with the ice that settled out as the ice melted (ablation till or melt-out till) or moved as localized mud flows (flow till). Subglacial till, such as lodgement till, formed beneath glacial ice.

Glaciofluvial deposits are materials moved by glaciers and subsequently carried, sorted, and deposited by meltwaters flowing from the ice. *Outwash* is a parent material term for the detritus (chiefly sand and gravel) removed or “washed out” from a glacier by meltwater streams and deposited beyond the ice front or end moraine. The coarsest material was deposited nearer the ice. This outwash commonly forms on plains, valley trains, outwash terraces, or deltas in drainageways or in relict glacial lakes. Some outwash terraces may extend far beyond the farthest advance of the ice. Near moraines or in disintegration moraine landscapes, sorted glaciofluvial material may form kames, eskers, and crevasse fills.

Glacial beach deposits consist of rock fragments and sand. They mark the locations of relict shorelines (i.e., strandlines) of former glacial lakes. Depending on the character of the original drift, beach deposits may be sandy, gravelly, cobbly, or stony.

Glaciolacustrine deposits are also derived from glaciers but were reworked and laid down in glacial lakes. These deposits range from fine clay to sand. Many of them are stratified or varved. A *varve* is the pair of deposition laminae for a calendar year. The finer portion reflects lower energy deposition during the cold season, and the slightly coarser portion reflects higher energy deposition during the warmer season when runoff is greater and wave action occurs.

In many places, it is difficult to distinguish between the different kinds of glacial sediments. For example, pitted outwash plains can be difficult to distinguish from sandy till in recessional moraines and wave-cut till can be difficult to distinguish from lacustrine material. Typically, even the most subtle differences can be identified from multiple, well planned field observations. This information is used to accurately determine the geomorphic setting and its associated sediments. Careful observations and descriptions of parent material, stratification, coarse fragment distribution, and the surface forms in which they occur provide hard evidence needed for correct conclusions. However, some situations are not fully understood at present because of their complexity or incomplete scientific knowledge.

Periglacial deposits have several major types. Cryoturbates are deposits of sediments that have been mixed or preferentially sorted by seasonal frost heave, partial melting and refreezing of permafrost, or other non-glacial ice displacement processes. These processes can organize sediments in several ways. Internally, the materials typically exhibit convolutions or low-grade internal sorting, unlike the more horizontal layering typical of mineral soils in warmer climates. Surficial sorting, particularly of coarse fragments, can take the form of polygons or stripes or other patterned ground. Solifluction deposits consist of heterogeneous mixtures of textures, including rock fragments. The orientation of the rock fragments indicates the slow downslope movement that resulted in surficial lobes, sheets, and terraces. Solifluction deposits form in response to seasonal or partial thawing of the near surface “active zone.”

Periglacial parent materials can have wide aerial extent. Active or recent periglacial deposits occur most extensively at high latitudes or at high elevations outside of, or otherwise unaffected by, glacial ice. Relict solifluction deposits also widely occur in the form of relict patterned ground in association with former continental glaciated areas in mid latitudes.

Mass wasting (mass movement) deposits.—Some materials are transported primarily or completely by gravity. Transport can occur extremely quickly or gradually. *Landslide deposits* is a generic term that includes all forms of landslide materials. These deposits can be more explicitly identified based on the main mode of movement (table 2-8).

Table 2-8

Types of Landslide Deposits

Movement types	Deposit attributes
Fall deposits	Free fall, bouncing or rolling
Topple deposits	Forward rotation over a basal pivot point
Slide deposits: Rotational landslide	Backward rotation around a pivot point above the ground surface
Slide deposits: Translational slide	Mass lateral displacement along a planar slip face
Spread deposits	Layers plastically extruded by liquefaction
Flow deposits	Wet or dry mass flow that behaves as a viscous liquid

Each of these movement types can be further subdivided to indicate the dominant kind of material moved: rock (consolidated bedrock masses), debris (unconsolidated material rich in rock fragments), or earth (dominantly fine-earth material). (See Mass Movement (Wasting) Types table in Schoeneberger et al., 2012.) These terms are useful in specifying different levels of detail needed to identify areas according to their associated deposits. They are also used to convey the composition of the present materials, which impacts land management decisions.

Other kinds of gravity-related deposits are widely recognized. *Colluvium* is poorly sorted slope sediments that have been transported and accumulated along or at the base of slopes, in depressions, or along small streams primarily due to gravity, soil creep, and slope wash processes. Accumulations of rock fragments at the base of rock outcrops are called *talus*. Rock fragments in colluvium are typically very angular to sub-rounded due to relatively short transport distances and the limited abrasion associated with the process. In contrast, rock fragments in alluvium and glacial outwash are rounded to well rounded and waterworn.

Organic deposits.—Organic deposits are material dominated by carbon-rich plant or organism detritus. The organic material accumulates more rapidly than it decomposes. This unconsolidated material is commonly associated with, but not restricted to, wet soil or subaqueous conditions. Organic deposits can persist in extremely dry settings or under other conditions that reduce or eliminate microbial decomposition, such as low oxygen or low pH (acidic). These latter conditions can produce various types of organic accumulations that may become the soil parent material generically called “organic materials.” Organic deposits can be further defined according to the dominant plant material present, such as woody, herbaceous, grassy, or mossy. Different terms are used to modify an associated soil texture (e.g., mucky, peaty). Terms used *in lieu* of texture for organic materials include muck, peat, and highly decomposed organic materials (see chapter 3).

Some organic materials occur as alternating layers of different kinds that reflect the dominant vegetative cover at the time of deposition. Others are combinations of peat and mineral materials. In some places, organic materials cap, are intimately mixed with, or are discretely interlayered with volcanic ash, marl, alluvium, or eolian sands. Descriptions of organic material (see chapter 3) should include labels (e.g., woody organic materials) or notations identifying the origin and dominant botanical composition, to the extent that they can be reasonably inferred.

Volcanic deposits.—Volcanic eolian deposits, such as ash and pumice, are treated separately from other eolian parent materials because of their unique mineralogy and depositional dynamics. Tephra, volcanic ash, pumice, and cinders are unconsolidated igneous sediments that were ejected during volcanic eruptions and moved from their place of origin. Most have been reworked by wind and, in some places, by water. *Tephra* is a broad, generic term referring to any form of volcanic ejecta. Various subdivisions are recognized and should be used when possible. *Ash* is volcanic ejecta smaller than 2 mm. It can be subdivided into fine ash (< 0.06 mm) and coarse ash (> 0.06 and < 2 mm). *Pumice* is volcanic ejecta larger than ash (> 2 mm) that has a low specific gravity (< 1.0). *Cinders* are volcanic ejecta larger (> 2 mm and < 64 mm) than ash and heavier (specific gravity > 1.0 and < 2.0) than pumice. (See Pyroclastic Terms table in Schoeneberger et al., 2012.)

Anthropogenic deposits.—Human-transported material is a general term for solid phase organic or mineral material that can function as soil or soil-like material. It has been mixed and moved from a source area to a new location by purposeful human activity, usually with the aid of machinery or hand tools. There has been little or no subsequent reworking by wind, gravity, water, or ice. Human-transported materials are most commonly associated with building sites, mining or dredging operations, landfills, or other activities that result in the formation of a constructional anthropogenic landform. Anthropogenic material differs from natural deposits in that its internal composition and stratigraphic arrangements depend upon the emplacement methods, tools, and intentions of people. It is generally more variable and less predictable in its content and configuration than material emplaced by natural processes. Nonetheless, it can be described and broadly quantified in ways similar to how natural materials are evaluated.

In database management, it is helpful of have an alphabetical master list of the many kinds of parent materials. The diverse kinds of parent materials can also be constructively arrayed within subsets based upon the dominant geomorphic processes that erode, transport, or deposit them (see "Parent Material" section in Schoeneberger et al., 2012). Table 2-9 lists parent material groups based on geomorphic process or setting.

Table 2-9

General Groups of Parent Materials Based on Geomorphic Process or Setting

General groups	Specific examples
Anthropogenic deposits	Dredge spoil, mine spoil, earthy fill
Eolian deposits (nonvolcanic)	Eolian sands, loess
Glacial and periglacial deposits	Till, solifluction deposit
In-place deposits (nontransported)	Residuum, saprolite
Mass wasting deposits	Mudflow deposit, talus
Miscellaneous deposits	Diamicton, gypsite
Organic deposits	Diatomaceous earth, grassy organic materials
Volcanic deposits	Andesitic ash, pumice
Water-laid or water-transported deposits	Alluvium, lacustrine deposit

These subsets compliment and loosely parallel the geomorphic environment categories presented in the Geomorphic Description System used by the NCSS (Schoeneberger et al., 2012). Soil parent materials should generally relect the dominant geomorphic environment and vice versa.

Multiple Parent Materials

Soil is commonly composed of layers of several different types of parent materials (e.g., colluvium over residuum) that are identifiable in the soil's stratigraphy. For example, till is covered by a mantle of loess in many places. Thick mantles of loess are easily recognized, but very thin (e.g.,< 25 cm) mantles may be so altered by soil-building processes, such as pedoturbation, that they can scarcely be differentiated from the underlying till. The contact between substantially different (contrasting) parent materials in a soil is called a lithologic discontinuity. It should be documented using horizon description nomenclature (see chapter 3) and other descriptive conventions.

Unconsolidated contrasting soil material may differ in pore-size distribution, particle-size distribution, mineralogy, bulk density, or other properties. Some of the differences may not be readily observable in the field. Some deposits are clearly stratified, such as some lake sediments and glacial outwash, and the discontinuities are sharply defined.

The primary deposition differences of multiple, contrasting parent materials can be confused with the effects of soil formation. Silt content may decrease regularly with increasing depth in soils presumed to have formed in till. The higher silt content in the upper part of these soils can be explained by factors other than soil formation. In some of these soils, small amounts of eolian material may have been deposited on the surface over the centuries and mixed with the underlying till by insects and rodents or freeze-thaw action. In others, the silt distribution may reflect water sorting.

Inferences about contrasting properties inherited from differing layers of geologic material may be noted when the soil is described. Generally, each identifiable layer that differs clearly in properties from adjacent layers is recognized as a horizon or subhorizon. Whether it is recognized as a discontinuity or not depends upon its degree of contrast with overlying and underlying layers and its thickness.

A pragmatic balance is needed between identifying the dominant parent material layer(s) in a soil and not becoming overwhelmed by excessive detail. While there are no rigid criteria, such as a thickness minimum, it is particularly important to identify layers that are physically contrasting enough and thick enough to substantively affect internal water flow. There are several widely recognized exceptions for which numerous sediment layers are not comprehensively described. For deposits that are intrinsically highly stratified, whose lateral continuity is intermittent, it is impractical to identify or sample every thin layer (lamina). For finely laminated alluvium or tephra deposits, only the larger, aggregate layers are identified and sampled as composites (bulked). Minor layers (laminae) within larger layers are noted but typically are not comprehensively documented nor sampled individually.

Bedrock

The term "bedrock" as used in soil survey refers to continuous, coherent (consolidated) rock. It can be a physical barrier within the solum that limits rooting depth or the immediate parent material source for residual soils. Bedrock helps to determine local topography and the soils that form across it. It can also indirectly impact soils. If fairly close to the base of the solum, bedrock can affect the presence or absence of ground water and preferential flow direction, depending upon its porosity. It can be a determinant factor in slope stability (tendency for landslides) or impact excavation, such as soil suitability for basements and road construction. Identifying the bedrock, whether its influence is direct or indirect, is essential in understanding the intrinsic chemical and physical behavior of both the rock material itself and its soil or regolith derivatives. Bedrock also has a major impact on soil geography and the accurate prediction of it. Boundaries between types of bedrock commonly, but not always, coincide with changes in overlying soil types. Therefore, accurate recognition and documentation of bedrock is generally essential. In some natural settings, the documentation of bedrock may be problematic, impractical, or unnecessary. Bedrock is not recorded if it does not exert substantial influence on the soil. An example is bedrock that is deeply buried by regolith, such as till, basin fills, and coastal or lacustrine sediments.

Geological materials need to be defined in accordance with the accepted standards and nomenclature of geology. The accepted, authoritative names of the geological formations are recorded in soil descriptions. As soil research progresses, there is an increasing number of correlations between particular geological formations and the mineral and nutrient content of parent materials and soils. Examples include: (1) certain terrace materials and deposits of volcanic ash that are different in age or source, but otherwise indistinguishable, may vary widely in content of cobalt; (2) the phosphorus content of otherwise similar soils may vary widely due to similar limestones that can be distinguished in the field only by specific fossils.

Igneous rocks formed by the solidification of magma that originated within Earth's upper mantle. There are two main types based on their mode of formation—intrusive and extrusive. Intrusive (syn., plutonic) types form at considerable depth in the Earth's crust and possess a coarse grain texture due to the slow cooling of magma. Examples of intrusive igneous rocks that weather to soil parent material are granite, diorite, and gabbro. Extrusive (syn., volcanic) types form on the Earth's surface or at very shallow depth and possess a fine grain texture due to the rapid cooling of magma. Examples of common extrusive igneous rocks are rhyolite, andesite, and basalt.

Sedimentary rocks formed from sediments laid down in previous geological ages. The principal broad groups of sedimentary rocks are clastic, chemical, and organic. Examples of rock lithologies in the clastic group are shale, sandstone, and conglomerate; examples of those in the chemical group are limestone, gypsum rock, and travertine; and examples of those in the organic group are coal and diatomite. There are many varieties of these lithologies. For example, chalk is a soft variety of limestone. Many lithologies are intermediate between the broad groups. Examples are calcareous sandstone and arenaceous limestone.

Metamorphic rocks resulted from profound alteration of igneous and sedimentary rocks by heat and pressure. General classes of metamorphic rocks important as parent material are gneiss, schist, slate, marble, quartzite, and phyllite.

Kinds of Bedrock

Kind is the most important bedrock feature to describe. It indicates the general composition of the rock and how the rock and its weathering products are likely to behave. Soil survey follows standard conventions for rock type compositions and names (Neuendorf et al., 2005). There is a large number of officially recognized rock types. They are very detailed and can be functionally cumbersome for soil survey. Subsequently, soil survey tends to focus on broader categories and common rock types, particularly those found in the near surface environment. More obscure or minor rock types can be recognized if they have important economic or environmental impact. Some databases maintain long alphabetical master lists of bedrock. A helpful way to arrange the large number and variety of bedrock kinds is to separate them into widely recognized subsets, such as igneous, metamorphic, and sedimentary (Schoeneberger et al., 2012; USDA-NRCS, 2016b). In addition to bedrock kind, descriptions of bedrock should include information about the spacing of fractures, degree of weathering, and depth to contact (if within or near the solum).

The general groups of bedrock types described earlier can be subdivided or rearranged slightly to provide groups of bedrock types commonly pertinent to soils:

Igneous-intrusive.—Examples are anorthrosite, diabase, and granite.
Igneous-extrusive.—Examples are a'a lava, andesite, and basalt.
Igneous-pyroclastic.—Examples are pyroclastic flow, tuff, and volcanic breccia.
Metamorphic.—Examples are amphibolite, gneiss, and schist.
Sedimentary-clastics.—Examples are arenite, argillite, and mudstone.
Interbedded.—Examples are limestone-sandstone, sandstone-shale, and shale-siltstone.
Evaporites, organics, and precipitates.—Examples are tufa, coal, and limestone.

Depth to Bedrock

Depth to bedrock is a crucial feature because of its impact on plant growth, internal water dynamics and direction, and land management. This is particularly true for agricultural soils if hard bedrock is within 2 meters of the surface. Bedrock can limit rooting depth, reduce the potential soil water supply, affect internal water flow, and impact various mechanical activities, such as deep ripping, foundation excavation, fence post placement, and suitability for basements. The depth from the ground surface to the contact with bedrock should be recorded.

Fracture Interval

Most bedrock contains a natural joint or crack network that functions as by-pass flow routes for internal water. These fractures can vary substantially in the amount of water they are able to transmit and can potentially affect pond integrity, internal pollutant movement, and water well yields. If observable, the average horizontal spacing between vertical rock joints in the bedrock layer is described.

Weathering

Not all bedrock is chemically and/or physically altered from its pristine state to the same extent. Weathering generally increases porosity and the water-holding capacity and reduces bulk density and coherency. A weathering class (e.g., slight, moderate, strong) can be assigned to record the bedrock's subjective extent of weathering as compared to its presumed unweathered state.

Lithostratigraphic Units

Lithostratigraphic units are mappable rock or sediment bodies. In geochronology, younger units overly older units (law of superposition). Regolith units, both unconsolidated material and bedrock units, are identified and named according to standard conventions of the International Stratigraphic Code (e.g., North American Commission on Stratigraphic Nomenclature, 2005). Table 2-10 lists these units in descending rank. This naming system provides a standard, shorthand method of identifying and concisely communicating information on strata and rock type. It aids recognition of differences in geology and the soils developed in or on them. Some soils, particularly residual soils, can be linked to specific bedrock units. Other soils, such as loess, can occur across multiple bedrock units if their lithostratigraphic unit is not bedrock constrained. If possible, the hierarchical lithostratigraphic units at a site should be recorded (Schoeneberger et al., 2012).

Table 2-10

Lithostratigraphic Units and Their Hierarchical Rank and Definition

- *Supergroup.*—The broadest lithostratigraphic unit. A supergroup is an assemblage of related, superposed groups, or groups and formations. It is most useful for regional synthesis.
    - *Group.*—The second ranking lithostratigraphic unit. A group is a named assemblage of superposed formations and may include unnamed formations. It is useful for small-scale (broad) mapping and regional stratigraphic analysis.
        - *Formation (or Geologic Formation).*—The basic lithostratigraphic unit used to describe, delimit, and interpret sedimentary, extrusive igneous, metavolcanic, and metasedimentary rock bodies (excluding metamorphic and intrusive igneous rocks). It is based on lithic characteristics and stratigraphic position. A formation is commonly, but not necessarily, tabular and stratified and is of sufficient extent to be mappable at the Earth's surface or traceable in the subsurface at conventional mapping scales.
            - *Member.*—The formal lithostratigraphic unit next in rank below a formation and always part of a formation. A formation need not be divided selectively or entirely into members. A member may extend laterally from one formation to another.

- *Lens (or Lentil).*—A specific type of member. A lens is a geographically restricted member that terminates on all sides within a formation.
- *Tongue.*—A specific type of member. A tongue is a wedge-shaped member that extends beyond the main formation boundary or that wedges or pinches out within another formation.
  - *Bed.*—The smallest lithostratigraphic unit of sedimentary rock. A bed is a subdivision of a member based upon distinctive characteristics or economic value (e.g., coal member). Members need not be divided selectively or entirely into beds.
  - *Flow.*—The smallest lithostratigraphic unit of volcanic rock. A flow is a discrete, extrusive, volcanic body distinguishable by texture, composition, superposition, and other criteria.

Erosion

Erosion is the detachment and movement of soil material. The process may be natural or accelerated by human activity. Depending on the local landscape and weather conditions, erosion can range from very slow to very rapid. Loss of the soil surface layer has a direct detrimental impact on site productivity and on off-site sedimentation and nutrient inputs. It is especially important to evaluate for environmental and agronomic purposes. The dominant kind and degree (relative magnitude) of accelerated erosion at the site should be estimated.

Natural Erosion

Naturally occurring erosion sculptured landforms on the uplands and built landforms on the lowlands. Its rate and distribution in time control the age of land surfaces and many of the internal properties of the soils on them. The formation of the Channel Scablands in the State of Washington is an example of extremely rapid natural, or geologic, erosion. The broad, nearly level interstream divides on the Coastal Plain of the southeastern United States are examples of areas with very slow or no natural erosion.

Landscapes and their soils are evaluated from the perspective of their natural erosional history. Evidence that material has been moved and redeposited, including buried soils, stone lines, and deposits of windblown material, is helpful in understanding natural erosion history. Thick weathered zones that developed under earlier climatic conditions may have been exposed and become the material in which new soils formed. In landscapes of the most recently glaciated areas, the consequences of natural erosion, or lack of it, are less obvious than where the surface and the landscape are early Pleistocene or even Tertiary in age. However, even on the landscapes of the most recent glaciation, postglacial natural erosion may have redistributed soil materials on the local landscape. Natural erosion is an important process that affects soil formation and, like human-induced erosion, can remove all or part of soils formed in the natural landscape.

Accelerated Erosion

Accelerated erosion is largely the consequence of human activities, primarily those that result in a loss of soil cover, such as tillage, grazing, and cutting of timber. Kinds are listed in table 2-11 and discussed below.

Table 2-11

Kinds of Accelerated Erosion

Erosion kind	Criteria
Wind	Deflation by wind
Water:	Removal by running water
Sheet	Relatively uniform soil loss; no channels
Rill	Small channels (can be obliterated by conventional tillage)
Gully	Big channels (cannot be obliterated by conventional tillage)
Tunnel	Subsurface voids within soil that are enlarged by running water (i.e., piping)

The rate of erosion can be increased by events besides human activities. For example, fire that destroys vegetation can trigger erosion. Spectacular episodes of erosion, such as the soil blowing on the Great Plains of the central United States in the 1930s, have not all been due to human activities; frequent dust storms were recorded on the Great Plains before the region became a grain-producing area.

Accelerated erosion may not be easy to distinguish from natural erosion on some soils. A distinction can be made by studying and understanding the sequence of sediments and surfaces on the local landscape as well as by studying soil properties. For example, in some areas of the eastern United States, native forests were cut and burned to create cropland. In some places where the soils were particularly susceptible, this resulted in extensive soil erosion. The sediments from the uplands can be observed on adjacent flood plains as a sequence of layers that, in some places, are up to a few meters thick over a buried soil. The contact between the original soil surface and new sediments commonly is evidenced by numerous pieces of charcoal above the contact, which presumably originated from the burning of timber.

Wind Erosion

The term “wind erosion,” as used in this manual, in soil science generally, and by many geologists, indicates the detachment, transportation, and deposition of soil particles by wind, not the sculpture of rocks by windblown particles. Wind erosion in regions of low rainfall can be widespread, especially during periods of drought. Unlike water erosion, wind erosion is generally not related to slope gradient. The hazard of wind erosion is increased by removing or reducing the amount of vegetation. When winds are strong, coarser particles are rolled, or swept along, on or near the soil surface and finer particles are forced into the air. The particles are deposited in places sheltered from the wind. When wind erosion is severe, the sand particles may drift back and forth locally with changes in wind direction while silt and clay are carried away. Small areas in which the surface layer has blown away may be associated with areas of deposition in such an intricate pattern that the two cannot be identified separately on soil maps.

Water Erosion

Water erosion results from the removal of soil material by flowing water, including the detachment of soil material by the impact of raindrops. The soil material is suspended in runoff water and carried away. Some sediment may be carried just a few meters before being deposited, while other sediment may be completely removed from the site. Four kinds of accelerated water erosion are commonly recognized: sheet, rill, gully, and tunnel (piping).

Sheet erosion is the more or less uniform removal of soil from an area without the development of conspicuous water channels. The channels are tiny or tortuous, exceedingly numerous, and unstable. They enlarge and straighten as the volume of runoff increases. Sheet erosion is less apparent, particularly in its early stages, than other types of erosion. It can be a problem for soils that have a slope gradient of only 1 or 2 percent; however, it is generally more of an issue as slope gradient increases.

Rill erosion is the removal of soil as concentrated runoff cuts many small, but conspicuous, channels. It is intermediate in degree between sheet and gully erosion. The channels are shallow enough that they are easily obliterated by tillage. After an eroded field has been cultivated, determining whether soil losses resulted from sheet or rill erosion is generally impossible.

Gully erosion is the removal of soil by water along the line of flow. Gullies form in exposed natural drainageways, in plow furrows, in animal trails, in vehicle ruts, between rows of crop plants, and below broken human-made terraces. Unlike rills, they cannot be obliterated by ordinary tillage. Deep gullies cannot be crossed with common types of farm equipment.

Gullies and gully patterns vary widely. V-shaped gullies form in material that is equally or increasingly resistant to erosion with increasing depth. U-shaped gullies form in material that is equally or decreasingly resistant to erosion with depth. As the substratum is washed away, the overlying material loses its support, falls into the gully, and is also washed away. Most U-shaped gullies become modified toward a V shape once the channel stabilizes and the banks begin to crumble and slump. The maximum depth to which gullies are cut is governed by resistant layers in the soil, by bedrock, or by the local base level. Many gullies develop headward, i.e., they extend up the slope as the gully deepens in the lower part.

Tunnel erosion may occur in soils with subsurface horizons or layers that are more subject to entrainment than the surface horizon or layer. Through ponded infiltration, the free water enters into the soil's surface-connected macropores. Desiccation cracks and rodent burrows are examples of macropores that may initiate the process. The soil material incorporated into the moving water travels downward within the soil profile, and if there is an outlet, may move out of it completely. As a result, tunnels (also referred to as pipes) form, enlarge, and coalesce. The portion of the tunnel near the inlet may enlarge disproportionately to form a funnel-shaped feature, commonly referred to as a "jug." This phenomenon is called "piping" or "jugging" and occurs especially in areas with appreciable amounts of exchangeable sodium.

Sediment carried by water typically is deposited wherever the water's velocity slows, such as at the mouth of gullies, at the base of slopes, along streambanks, on alluvial plains, in reservoirs, and at the mouth of streams. Water moving rapidly can deposit stones. As it slows, it deposits cobbles, followed by gravel, sand, and finally silt and clay. The slope length for sediment transport is the distance from the highest point on the slope where runoff may start to where the sediment in the runoff would be deposited.

Estimating the Degree of Erosion

Soil examinations can estimate the degree to which accelerated erosion has modified the soil. However, estimating the amount of surface soil that is no longer present can be very difficult. This is generally most feasible if sufficient areas of the soil are known to be little affected by past accelerated erosion and can be used for comparison studies. The recognition of eroded and uneroded phases of a soil is useful if at least some soil properties making up the eroded phase are different enough from those of the uneroded phase to impact the soil's use and management. The eroded soil is identified and classified on the basis of the properties of the soil that remains and not on what was presumed to have been present in the past. In some cases, the eroded soil may classify differently from the uneroded soil. An estimate of the soil lost is described. Eroded soils are defined so that the boundaries on the soil maps separate soil areas with different use suitabilities and different management needs.

The depth to a reference horizon or soil characteristic in areas under a use that has minimized erosion are compared to the same properties in areas under uses that have accelerated erosion. For example, a soil that supports native grass or large trees with no evidence of cultivation could be compared with the same or similar soil that has been cleared and cultivated for a relatively long time. The depth to reference layers is measured from the top of the mineral soil because cultivation destroys organic horizons at the surface.

The depth to a reference layer must be interpreted in terms of recent soil use or history. The upper parts of many forested soils have roots that make up as much as one-half of the soil volume. When these roots decay, the soil settles. Removal of rock fragments can also lower the surface. Cultivation may cause differences in thickness of layers. The thickness of surficial zones that have been bulked by tillage should be adjusted downward to what they would be under natural conditions.

The thickness of a plowed layer cannot be used as a standard for either losses or additions of material because, as a soil erodes, the plow cuts progressively deeper. Nor can the thickness of the uncultivated and uneroded A horizon be used as a standard for all cultivated soils, unless the A horizon is much thicker than the plow layer. If the horizon immediately below the plowed layer of an uneroded soil is distinctly higher in clay than the A horizon, the plow layer becomes progressively more clayey under continued cultivation as erosion progresses. In this case, the texture of the plow layer can be a criterion of erosion. Comparisons must be made on comparable slopes. Near the upper limit of a soil's range of slope gradient, horizons may normally be thinner than near the lower limit.

Roadsides, cemeteries, fence rows, and similar uncultivated areas that make up a small part of the landscape or were subject to unusual cultural histories must be used cautiously for setting standards. In these areas, the reference standards for surface layer thickness are generally set too high. In naturally treeless areas or in areas cleared of trees, dust may collect in fence rows, along roadsides, and in other small uncultivated areas that are covered with grass or other stabilizing plants. This accumulated dust may cause the surface horizon to become several centimeters thicker in a short time.

For soils having clearly defined horizons, differences due to erosion can be accurately determined by comparison to undisturbed or uncultivated sites. Guidelines for estimating erosion for soils with a thin A horizon and little or no other horizon are more difficult to establish. After the thin surface layer is gone or has been mixed with underlying material, few clues remain for estimating the degree of erosion. One must rely on the physical conditions of the material in the plowed layer, the appearance and amount of rock fragments on the surface, the number and shape of gullies, and similar evidence. For many soils having almost no horizon expression, attempting to estimate the degree of erosion serves no useful purpose.

Precise estimates of the amount of soil lost from a site based on comparison studies with a similar uneroded site are complicated by several factors. The goal is to establish map unit concepts that reflect the relative degrees of soil loss between eroded phases of a soil and that result in some significant differences in the use and management of the soils based on their current properties.

Degree Classes for Accelerated Erosion

The degree classes for accelerated erosion discussed below and listed in table 2-12 apply to both water and wind erosion. They are not applicable to landslip or tunnel erosion. The classes pertain to the proportion of upper horizons that has been removed. These horizons may range widely in thickness; therefore, the absolute amount of erosion is not specified.

Table 2-12

Degree Classes for Accelerated Soil Erosion

Degree class	Criteria: Estimated % loss of the original combined A + E horizons, or the estimated loss of the upper 20 cm (if original, combined A + E horizons are < 20 cm thick)
None	0 %
1	> 0 to 25 %
2	25 to 75 %
3	75 to 100 %
4	> 75 % and total removal of the A horizon

Class 1.—This class consists of soils that have lost some, but on average less than 25 percent, of the original A and/or E horizons or of the uppermost 20 cm if the original A and/or E horizons were less than 20 cm thick. Throughout most of the area, the thickness of the surface layer is within the normal range of variability of the uneroded soil. Less than 20 percent may consist of scattered small areas with a significantly modified surface layer.

Evidence for class 1 erosion includes: (1) a few rills, (2) accumulation of sediment at the base of slopes or in depressions, (3) scattered small areas where the plow layer contains material from below, and (4) evidence of the formation of widely spaced, deep rills or shallow gullies without consistently measurable reduction in thickness or other change in soil properties between the rills or gullies.

Class 2.—This class consists of soils that have lost, on average, 25 to 75 percent of the original A and/or E horizons or of the uppermost 20 cm if the original A and/or E horizons were less than 20 cm thick. Throughout most cultivated areas of class 2 erosion, the surface layer consists of a mixture of the original A and/or E horizons and material from below. Some areas may have intricate patterns, ranging from somewhat over-thickened surface layers where sediment has accumulated locally to small areas of uneroded soils on gentle slopes or severely eroded soils on steeper, convex slopes. Where the original A and/or E horizons were very thick, little or no mixing of underlying material may have taken place.

Class 3.—This class consists of soils that have lost, on average, 75 percent or more of the original A and/or E horizons or of the uppermost 20 cm if the original A and/or E horizons were less than 20 cm thick. In most areas, material below the original A and/or E horizons is exposed at the surface, especially in convex positions in cultivated areas; the plow layer consists entirely or largely of this material. Even where the original A and/or E horizons were very thick, at least some mixing with underlying material generally took place. Despite the generally universal loss of surface soil, some areas exhibit intricate patterns, ranging from somewhat over-thickened surface layers where sediment has accumulated locally to small areas of only slightly eroded soils, generally where slopes are relatively gentle.

Class 4.—This class consists of soils that have lost all of the original A and/or E horizons or the uppermost 20 cm if the original A and/or E horizons were less than 20 cm thick. In most areas, some or all of the deeper horizons have been removed throughout the majority of the area. The original soil can be identified only in small areas. Some areas may be smooth, but most have an intricate pattern of gullies.

Land Cover

The type of land cover around the site where a soil is described should be recorded. As with other descriptive terms, it is best to use standard terms consistently. The NCSS has adopted a set of general terms that includes land cover kinds, such as *artificial cover, barren land, crop cover, shrub cover, grass/herbaceous cover, tree cover,* and *water*. Subtypes within these general classes are also recorded. See Schoeneberger et al. (2012) for the land cover types and subtypes used.

In addition to recording the overall land cover condition at the site, more detailed analysis can be done to provide quantitative estimates of the surface cover at the site. The ground surface of most soils is covered by vegetation to some extent at least part of the year. In addition, rock fragments form part of the mineral material at the surface of many soils. The vegetal material that is not part of the surface horizon and the rock fragments together form the ground surface cover. The proportion of cover, along with its characteristics, is very important in determining a soil's thermal properties and resistance to erosion.

At one extreme, estimation of cover can be made visually without quantitative measurement. At the other extreme, transect techniques can be used to make an almost complete modal analyses of the ground surface. If the ground surface is relatively permanent, more effort in documentation is justified. In many cases, a combination of rapid visual estimates and transect techniques is appropriate.

The ground surface may be divided into fine earth and material other than fine earth. The latter consists of rock fragments and both live and dead vegetation. Vegetation is separated into *canopy* and *noncanopy* (litter). A canopy component has a relatively large cross-sectional area capable of intercepting rainfall compared to the area near enough to the ground surface to affect overland water flow. When determining susceptibility to erosion, both canopy and noncanopy vegetation are considered.

The first step in evaluation is determining the components (typically one to three) of the ground surface cover. A common three-component land surface consists of trees, bushes, and areas between the two. The areal proportion of each component must be established, such as by transect. If a canopy component is present, the area within the tree drip line (edge of where water drips from trees and onto the ground) is determined as a percent of the ground surface. For each canopy component, the effectiveness must be established. *Effectiveness* is the percent of vertical raindrops that would be intercepted. The canopy effectiveness is typically estimated visually, but a spherical densitometer may be used. In addition to the canopy effectiveness, the mulch must be identified for each component.

Transect techniques may be used to determine the mulch percentage. The mulch can be subdivided into rock fragments and vegetation. From the areal proportions of the components and their respective canopy efficiencies and mulch percentages, the soil-loss ratio may be computed for the whole land surface (Wischmeier and Smith, 1978). Other observations may include the percent of kinds of plants, size of rock fragments, amount of green leaf area, and aspects of color of the immediate surface that may affect absorption of radiant energy in an area.

Vegetation

It is important to evaluate and record details about the vegetative community of a site, particularly in non-agricultural settings, such as rangeland, marshes, and forests. Plants reflect the integrated effects of controlling water dynamics, climate, native fertility, human intervention, and other factors upon the soil. Baseline vegetation information centers on the plant species present and the extent of the area that they cover.

Typically, the dominant plant species present are identified and documented in descending order of prominence. The scientific name is used along with, or *in lieu* of, the common name. Common plant names are not preferred as they may not be unique. A species may be known by multiple common names in a region, depending upon local cultures and languages spoken. The appropriate scientific plant symbol (USDA-

NRCS, 2016c) is also recorded, for example, ANGE (*Andropogon gerardii,* or big bluestem). The amount of ground covered by each plant species recorded at the site is also estimated or measured.

Ecological Sites

Soils and natural vegetative communities are generally closely related. For this reason, soil survey efforts commonly include the correlation of soil map unit components with ecological site information for an integrated natural resource inventory. In the United States, the soils are formally correlated to ecological sites (USDA-NRCS, 2016a).

An ecological site is a conceptual division of the landscape. It is defined as a distinctive kind of land based on recurring soil, landform, geological, and climate characteristics that differs from other kinds of land in its ability to produce distinctive kinds and amounts of vegetation and in its ability to respond similarly to management actions and natural disturbances. Ecological sites combine soils, climate, landform, vegetation, and hydrology into groupings subject to similar management and with similar response to disturbance. Ecological site descriptions provide characterization information for each site, state-and-transition models (USDA-NRCS, 2016a) that depict vegetation dynamics, and information on use and management. Appendix 4 discusses ecological site assessments.

In determining soil types and ecological sites, the vegetation that was on site during soil formation is very important. Use of soil information for descriptions of ecological dynamics, state-and-transition models, and management recommendations depends upon the best characterization of the vegetation community, including its history and current potential. Soil and vegetation (historic and potential) are the primary criteria for grouping ecosystems or ecosites at finer scales (USDA-FS, 2005). Existing vegetation does not always reflect historic or potential vegetation.

Soil-ecological site correlation establishes the relationship between soil components and ecological sites. Ecological sites are correlated on the basis of soils and the resulting differences in species composition, proportion of species, and total production of the historic climax plant community. In some cases, it is necessary to extrapolate data on the composition and production of a plant community for one soil to describe the plant community on a similar soil for which no data are available. The separation of two distinct soil taxonomic units does not necessarily delineate two ecological sites. Likewise, some soil taxonomic units occur over broad environmental gradients and may support more than one distinctive historic climax plant community. Changes in plant communities may be due to other influences, such as an increase or decrease in average annual precipitation.

Integrated Natural Resource Inventories

Integrated natural resource inventories incorporate several data elements, commonly at a variety of scales and with varying objectives. They typically use soil information as a key data element. Soil data, including maps, commonly provide a basis for spatial identification of combinations of features to define sites. Soil properties derived from soil survey data are grouped spatially and conceptually in logical units based on similarities in vegetative communities and in response to use and management. The concept of "site" has been used for many decades and includes a combination of several biotic and abiotic attributes. Ecological sites provide a conceptual framework in which data can be integrated for use by various agencies of the U.S. Government and other entities.

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CHAPTER 3

Examination and Description of Soil Profiles

Revised by Soil Science Division Staff.

Introduction

A description of the soils is essential in any soil survey. This chapter provides standards and guidelines for describing the soil. It contains standard technical terms and their definitions for most soil properties and features and provides information for describing the necessary related facts. For some soils, standard terms are not adequate and must be supplemented by a narrative. Some soil properties change through time. Many properties must be observed over time and summarized if one is to fully understand the soil being described and its response to short-term environmental changes. Examples are the length of time that cracks remain open, the patterns of soil temperature and moisture, and the variations in size, shape, and hardness of clods in the surface layer of tilled soils.

This chapter does not discuss every possible soil property. For some soils, other properties need to be described. Good judgment is needed to decide what properties merit detailed attention for any given pedon (sampling unit). Observations must not be limited by preconceived ideas about what is important.

Although the format of the description and the order in which individual properties are described are less important than the content of the description, a standard format has distinct advantages. The reader can find information more rapidly, and the writer is less likely to omit important features. Furthermore, a standard format makes data entry into a computer database more efficient. Any standardized forms need to allow enough space for all possible information.

Each investigation of the internal properties of a soil is made on a soil body with certain dimensions. The body may be larger than a pedon (e.g., a backhoe pit) or represent only a portion of a pedon (e.g., a sample from a hand auger). During field operations, many soils are investigated by examining the soil material removed by a sampling tube or auger. For rapid investigations of thin soils, a small pit can be dug and a section of soil removed with a spade. All of these are samples of pedons. Knowledge of the internal properties of a soil is derived mainly from studies of such samples. Samples can be studied more rapidly than entire pedons; consequently, a much larger number can be studied and for several more places. For many soils, the information obtained from a small sample amply describes the pedon from which it is taken. For other soils, however, important properties of a pedon are not observable in a smaller sample and detailed studies of the entire pedon are needed. Complete study of an entire pedon requires the exposure of a vertical section and the removal of horizontal sections layer by layer. Horizons are studied in both horizontal and vertical dimensions. The kind of exposure (e.g., bucket auger, push tube, small hand-dug pit, backhoe pit, road cut, etc.) should be identified in the soil description.

The information in this chapter, which focuses on the standards and guidelines for describing a soil profile in the field, is complemented by that provided in chapters 2, 6, 10, and 11. Chapter 2 provides information related to describing the site surrounding the soil profile. Chapter 6 discusses the use of proximal sensors to measure some soil properties quickly and efficiently at field and larger scales by using field-based electronic technology. Chapter 10 provides information specific to describing subaqueous soils. Chapter 11 discusses soils heavily impacted by human activity.

General Terms Used to Describe Soils

This section describes several of the general terms for internal elements of the soil. Other more specific terms are described or defined in the following sections.

Pedon

A pedon is a three-dimensional body of soil that has sufficient area (roughly 1 to 10 m^2) and depth (up to 200 cm) to be used in describing the internal arrangement of horizons and in collecting representative samples for laboratory analysis (see chapter 4). The pedon is the individual classified with Soil Taxonomy. Multiple pedons that have the same classification and occur together in landscapes are used in defining soil series. Conceptually, these contiguous pedons are called polypedons (see chapter 4).

Soil Profile

A soil profile is smaller than a pedon. It is exposed by a two-dimensional vertical cut through the soil. It is commonly conceived as a plane at right angles to the soil surface. In practice, a description of a soil profile includes soil properties that can be determined only by inspecting volumes of soil. However, the volume of soil described from a profile is almost always less than the volume of soil defined by a full pedon because observations of the soil profile are generally made to only a few decimeters behind the face of the exposed profile. A pedon description is commonly based on examination of a profile, and the properties of the pedon are inferred from the properties of the profile. The width of a profile ranges from a few decimeters to several meters or more. The size of the profile should be sufficient to include the largest structural units.

Soil Horizon

A soil horizon is a layer, approximately parallel to the surface of the soil, that is distinguishable from adjacent layers by a distinctive set of properties produced by the soil-forming processes (i.e., pedogenesis). The term "layer" is used instead of "horizon" if the properties are inherited from the parent material, such as sedimentary strata. Horizons, in contrast, display the effects of pedogenesis, such as the obliteration of sedimentary strata and accumulation of illuvial clay.

Solum

The solum (plural, sola) of a soil consists of a set of horizons that are related through the same period of pedogenesis. It includes all horizons now forming. It may also include a bisequum (discussed below). It does not include a buried soil or layer unless it has acquired some of its properties by currently active soil-forming processes. The solum of a soil is not necessarily confined to the zone of major biological activity. Its genetic horizons may be expressed faintly to prominently. A solum does not have a maximum or minimum thickness.

Solum and soils are not synonymous. Some soils include layers that are not affected by soil formation. These layers are not part of the solum. The number of genetic horizons ranges from one to many. An A horizon that is 10 cm thick overlying bedrock is by itself the solum. A soil that consists only of recently deposited new soil material or recently exposed soft sediment generally does not have a solum.

In terms of soil horizons as described in this chapter, a solum consists of O, V, A, E, and B horizons and their transitional horizons. Included are horizons with an accumulation of carbonates or more soluble salts if these horizons are either within, or contiguous to, other genetic horizons and are judged to be at least partly produced during the same period of soil formation.

The lower limit of the solum, in a general sense, in many soils should be related to the depth of rooting for perennial plants, assuming that water state and chemistry are not limiting. In some soils, the lower limit can be set only arbitrarily and is defined in relation to the particular soil. For example, horizons of carbonate accumulation are easily visualized as part of the solum in many soils in arid and semiarid environments. However, to conceive of cemented horizons of carbonates that may extend for 5 meters or more below the surface as part of the modern solum is more difficult. Such massive carbonate horizons represent pedogenesis over hundreds of thousands of years and are referred to as relict paleosols. Gleyed soil material begins in some soils a few centimeters below the surface and continues practically unchanged to a depth of many meters. Gleying immediately below the A horizon is likely to be related to the processes of soil formation in the modern soil. At great depth, gleying is likely to be relict or related to processes that are more geological than pedological. The same kind of problem exists for some deeply weathered soils—the deepest material penetrated by roots is very similar to the weathered material at much greater depth.

For some soils, digging deep enough to reveal all of the relationships between soils and plants is not practical. Plant roots, for example, may derive much of their moisture from fractured bedrock. Descriptions should indicate the nature of the soil-rock contact and determinations about the upper part of the underlying rock.

Not everyone will agree about the exact extent of the solum in some soils. For example, a certain level of subjectivity is involved in differentiating transitional BC or CB horizons from C horizons or in determining which properties observed in the soil are the product of active pedogenic processes. The concept of the solum remains useful for discussions about the nature of soils and soil profiles but is generally not used as a part of any technical definitions.

Sequum

A sequum (plural, sequa) consists of a B horizon and any overlying eluvial horizons. A single sequum is considered to be the product of a specific combination of soil-forming processes.

Most soils have only one sequum, but some have two or more. For example, a new sequence of horizons that meet the criteria for a Spodosol can form in the upper part of a previously existing Alfisol, producing an eluviated zone and a spodic horizon underlain by another eluviated zone overlying an argillic horizon. Such a soil has two sequa. Soils in which two sequa have formed, one above the other in the same deposit, are said to be *bisequal*.

If two sequa formed in different deposits at different times, the soil is not bisequal. For example, a soil having an A-E-B horizon sequence may form in material that was deposited over another soil that already had an A-E-B horizon sequence. Each set of A-E-B horizons is a sequum, but the combination is not a bisequum; the lower set is a buried soil. If the horizons of the upper sequum extend into the underlying sequum, the affected layer is considered part of the upper sequum. For example, the A horizon of the lower soil may retain some of its original characteristics and also have some characteristics of the overlying soil. In this case, the soils are also not considered bisequal; the upper part of the lower soil is the parent material of the lower part of the currently forming soil. In many soils the distinction cannot be made with certainty. If some of the C material of the upper sequum remains, the distinction is clear.

Studying Pedons

Site Selection

Pedons representative of an extensive mappable area are generally more useful than pedons that represent a transitional area to another soil. For detailed study of a soil, a pedon is tentatively selected and then examined preliminarily to determine whether or not it represents the desired segment of the soil's range. This is a critical step. Typically, only a few pedons can be studied in detail due to the time and expense involved in exposing, describing, photographing, and sampling soil profiles and performing necessary laboratory analysis. It is very important that the site selected for study is a representative sample of the overall soil body in the landscape because data from the site will be used to classify the soil pedon and correlate it with other similar pedons.

Information Recorded

For a soil description to be of greatest value, detailed information about its setting should be recorded (see chapter 2). Important items include location (identified by latitude and longitude, including datum, or another acceptable geographic location system), the part of the landscape that the pedon represents (i.e., landform, position on landform, any applicable microfeature), elevation, aspect, parent material, vegetation, land use, and erosion or other disturbance affecting the soil profile. The level of detail will depend on the objectives. A complete setting description should include information about the pedon and other soils conterminous with the pedon. It also may include information on any features that differ from the central concept of the soil series for which the described pedon is named (if a series has been defined).

The description of a body of soil in the field, whether an entire pedon or a soil profile within it, should record the kinds of horizons or layers, their depth and thickness, and the properties of each. Generally, external features, such as slope, surface stoniness, erosion, and vegetation, are observed for the area around the pedon, which is considered to be part of the same soil body. Internal features, such as color, texture, and structure, are observed from the study of the pedon.

Observing Pedons

In order to observe a pedon fully, including soil structure (size and kind), horizon boundary topography, and short-range variability in horizon thickness, a pit exposing a vertical face approximately 1 meter across to an appropriate depth (fig. 3-1) is adequate for most soils. Excavations associated with roads, railways, gravel pits, and other soil disturbances provide easy access for studying soils. Old exposures, however, must be used cautiously. In these areas, the soils can dry out or freeze and thaw from both the surface and the sides. In addition, the soil structure may be more pronounced than is typical, salts may have accumulated near the edges of exposures or been removed by seepage, plinthite may have irreversibly hardened to ironstone, or other changes may have taken place.

For hand- or backhoe-dug pits, care must be taken to ensure that the pit conforms to safety regulations. Loose sandy soils and wet soils are particularly susceptible to cave-ins.

After the sides of the pit are cleaned of all loose material disturbed by digging, the exposed vertical faces are examined, typically starting at the top and working downward, to identify significant changes in properties. Boundaries between layers are marked on the face of the pit, and the layers are identified and described.

Photographs should be taken after the layers have been identified but before the vertical section is disturbed in the description-writing process. An estimation of the volume of stones or other features also is done before the layers are disturbed.

Figure 3-1

A shallow soil pit with a face that has been cleaned and prepared for describing the soil profile. This soil (a Fibristel in Alaska) has been dug to the depth of permafrost (about 40 cm).

If bulk samples are to be collected for laboratory analysis, it generally is best to begin with the bottom layer and work upward. This prevents material from the upper layers falling onto the face of lower layers before they have been sampled.

A horizontal view of each horizon is useful. This exposes structural units that otherwise may not be readily observable from the vertical pit face. Patterns of color within structural units, variations of particle size from the outside to the inside of structural units, and the pattern in which roots penetrate structural units are commonly seen more clearly in a horizontal section (fig. 3-2).

Measuring Depth to and Thickness of Horizons and Layers

Soil Surface

When describing soil profiles, depth is measured from the soil surface. Generally, the soil surface is the top of the mineral soil. For soils with an O horizon (Oi, Oe, or Oa), it is the top of the O horizon. Fresh leaf or needle fall that has not undergone observable decomposition is excluded

Figure 3-2

A horizontal view (looking down) of a fragipan from a soil (a Fragiudalf) in Tennessee. The horizon has prismatic structure with gray seams between prisms and reddish redoximorphic features, mostly within the prisms. This view allows the structure and color patterns of the horizon to be easily observed. The exposed area is approximately 30 by 40 cm.

from the concept of an O horizon and may be described separately as a surface feature. Profile measurements begin below any fresh leaf or needle fall.

For soils that have a cover of 80 percent or more rock or pararock fragments (as in some areas of rubbly colluvial materials), the top of the soil is considered the mean height of the tops of the rock or pararock fragments. Depth measurements are taken from this height.

It is important to note that, when measuring depth and thickness for *taxonomic purposes,* the "mineral soil surface" is commonly specified as the datum to use in measurements. This essentially excludes any overlying O horizon and is therefore not synonymous with the soil surface as defined here for making soil descriptions. See *Keys to Soil Taxonomy* (Soil Survey Staff, 2014b or later version) for further information.

Depth Measurements

The depth to a horizon or layer boundary commonly differs within short distances, even within a pedon. The part of the pedon that is typical or most common is described. In the soil description, the horizon or layer designation is listed, followed by the values that represent the depths from the soil surface to the upper and lower boundaries (e.g., Bt1 - 8 to 20 cm). The depth to the lower boundary of a horizon or layer is the depth to the upper boundary of the horizon or layer beneath it. Variation in the depths of the boundaries is recorded in the description of the horizon or layer. The depth limits of the deepest horizon or layer described include only that part actually seen.

In some soils, the variations in depths to boundaries are so complex that the usual terms used to describe the boundary topography are inadequate. These variations are described separately, e.g., "depth to the lower boundary is mainly 30 to 40 cm, but tongues extend to depths of 60 to 80 cm." The lower boundary of a horizon or layer and the upper boundary of the horizon or layer below share a common irregularity.

Thickness Measurements

The thickness of each horizon or layer is the vertical distance between the upper and lower boundaries. Overall thickness may vary within a pedon, and this variation should be noted in the description. A range in thickness may be given, e.g., "thickness ranges from 20 to 30 cm." This range is not calculated from the range of upper and lower boundary depths. Instead, the range is calculated from evaluations across the exposure at different lateral points. For example, the upper boundary of a horizon may range in depth from 25 to 45 cm and the lower boundary from 50 to 75 cm. Taking the extremes of these two ranges, it is incorrect to conclude that the horizon thickness ranges from as little as 5 cm to as much as 50 cm when in fact it may be 20 to 30 cm in the field.

Designations for Horizons and Layers

Soils vary widely in the degree to which horizons are expressed. Relatively fresh parent materials, such as recent deposits of alluvium, eolian sands, or mantles of volcanic ash, may have no recognizable genetic horizons but may have distinct layers that reflect different modes of deposition. As soil formation proceeds, horizons in their early stages may be detected only by very careful examination. As horizons increase in age, they generally are more easily identified in the field. However, only one or two different horizons may be readily apparent in some very old, deeply weathered soils in tropical areas where annual precipitation is high. This section provides the standard nomenclature and definitions for a system used to assign symbols to soil horizons and layers.

Background and Concepts for Use of Designations

Different kinds of layers are identified by different symbols. Designations are provided for layers that have been changed by soil formation and for those that have not. Each horizon designation indicates either that the original material has been changed in certain ways or that there has been little or no change. The designation is assigned after comparison of the observed properties of the layer with properties inferred for the material before it was affected by soil formation. The processes that have caused the change need not be known; properties of soils relative to those of an estimated parent material are the criteria for judgment. The parent material inferred for the horizon in question, not the material below the solum, is used as the basis of comparison. The inferred parent material commonly is very similar to, or the same as, the soil material below the solum.

Designations show the describer's interpretations of genetic relationships among the layers within a soil. Layers do not need to be identified by symbols in order to make a good description, but the usefulness of soil descriptions is greatly enhanced by the proper use of designations. The designations provide a sort of shorthand nomenclature conveying the important properties observed by the person describing the soil as well as the genetic inferences made by that person regarding the formation of the soil. The definitions of the symbols provided below are generally more qualitative than quantitative. There is a small degree of subjectivity that allows some freedom for the describer to convey their theory of how the soil formed. There may be a certain level of inconsistency in the way different describers label the horizons of the same profile. For example, one describer may label a horizon "C" while another may label it "CB" or one may record a subtle lithologic discontinuity that another person does not observe.

Designations are not substitutes for descriptions. If both designations and adequate descriptions of a soil are provided, the reader has the interpretation made by the person who described the soil and also the evidence on which the interpretation was based.

Genetic horizons are not equivalent to the diagnostic horizons of Soil Taxonomy. Designations of genetic horizons express a qualitative judgment about the kind of changes that are believed to have taken place. Diagnostic horizons are quantitatively defined features used to differentiate taxa. Changes implied by genetic horizon designations may not be large enough to justify recognition of diagnostic criteria. For example, the designation "Bt" does not always indicate an argillic horizon. Furthermore, the diagnostic horizons may not be coextensive with genetic horizons.

Basic System of Horizon and Layer Designations

Four kinds of symbols are used in various combinations to designate horizons and layers:

Capital letters.—Used to designate the master horizons and layers.
Lowercase letters.—Used as suffixes to indicate specific characteristics of master horizons and layers.
Numbers.—Used both as suffixes to indicate vertical subdivisions within a horizon or layer and as prefixes to indicate discontinuities.
Special symbols.—Used to indicate layers formed in human-transported material or sequences of horizons having otherwise identical designations.

Master Horizons and Layers

The capital letters O, L, V, A, E, B, C, R, M, and W represent the master horizons and layers of soils. These letters are the base symbols to which other characters are added to complete the designations. Most horizons and layers have a designation using one capital letter symbol; some have two.

O Horizons or Layers

O horizons or layers are dominated by organic soil materials. Some are saturated with water for long periods; some were once saturated but are now artificially drained; and others have never been saturated.

Some O horizons or layers consist of slightly decomposed to highly decomposed litter (such as leaves, needles, twigs, moss, and lichens) that was deposited on the surface of either mineral or organic soils. Others consist of organic materials that were deposited under saturated conditions and have decomposed to varying stages. The mineral fraction of such material constitutes only a small percentage of the volume of the material and generally much less than half of its weight. Some soils consist entirely of materials designated as O horizons or layers.

An O horizon or layer may be at the surface of a mineral soil or, if buried, at any depth below the surface. A horizon formed by illuviation of organic material into a mineral subsoil is not an O horizon, although some horizons that formed in this manner contain a large amount of organic matter. Horizons or layers composed of limnic materials are not designated as O horizons.

L Horizons or Layers

L horizons or layers include both organic and mineral limnic materials that were either:

1. Deposited in water by precipitation or through the actions of aquatic organisms, such as algae and diatoms; or
2. Derived from underwater and floating aquatic plants and subsequently modified by aquatic animals.

L horizons or layers include coprogenous earth (sedimentary peat), diatomaceous earth, and marl. They are described only for Histosols (decomposed plant material) and not for mineral soils. They have only the following suffixes: *co, di,* or *ma* (described below). They do not have the subordinate distinctions of the other master horizons and layers.

V Horizons

V horizons are mineral horizons that formed at the soil surface or below a layer of rock fragments (e.g., desert pavement), a physical or biological crust, or recently deposited eolian material. They are characterized by the predominance of vesicular pores and have platy, prismatic, or columnar structure.

Porosity in a V horizon may include vughs and collapsed vesicles in addition to the spherical vesicular pores. V horizons formed in eolian material but may be underlain by soil horizons that formed in residuum, alluvium, or other transported materials. Because of their eolian origin, they are typically enriched in particle-size fractions ranging from silt through fine sand. Rarely, the V horizon is massive rather than structured. The structural arrangement of particles and vesicular porosity differentiates this horizon from the loose, unaltered eolian deposits that may occur above it. Underlying B horizons commonly have redder hues than the V horizon and lack vesicular pores (Turk et al., 2011).

Transitional and combination horizons with V horizon material occur in certain circumstances. Although uncommon, an AV or VA horizon may occur. It is both enriched in organic matter and contains vesicular pores. BV or VB horizons may indicate vesicular horizons that contain clay or carbonate coatings, or other properties of the underlying B horizon. EV or VE transitional horizons may also occur, especially in sodic soils.

Combination horizons of the V horizon with A, B, or E horizons may occur in bioturbated zones, such as shrub islands or areas where surface cover associated with the vesicular horizon (e.g., desert pavement) is patchy. Vesicular pores have been observed to reform quickly after physical disruption (Yonovitz and Drohan, 2009).

A Horizons

A horizons are mineral horizons that formed at the soil surface or below an O horizon. They exhibit obliteration of all or much of any original rock structure and show one or both of the following:

1. An accumulation of humified organic matter closely mixed with the mineral fraction and not dominated by properties characteristic of V, E, or B horizons; and/or
2. Properties resulting from cultivation, pasturing, or similar kinds of disturbance.

If a surface horizon has properties of both A and E horizons but the feature emphasized is an accumulation of humified organic matter, it is designated as an A horizon. Recent alluvial or eolian deposits that retain most of the original rock structure are not considered to be A horizons unless they are cultivated.

E Horizons

E horizons are mineral horizons in which the main feature is the eluvial loss of silicate clay, iron, aluminum, or some combination of these that leaves a concentration of sand and silt particles. They exhibit obliteration of all or much of the original rock structure.

An E horizon is commonly differentiated from an underlying B horizon in the same sequum by a color of higher value or lower chroma (or both), by coarser texture, or by a combination of these properties. In some soils the color of the E horizon is that of the sand and silt particles, but in many soils coatings of iron oxides or other compounds mask the color of the primary particles. An E horizon is most commonly differentiated from an overlying A horizon by its lighter color. It generally contains less organic matter than the A horizon. It is commonly near the soil surface, below an O, V, or A horizon, and above a B horizon. However, the symbol E can be used for eluvial horizons that are at the soil surface, are within or between parts of the B horizon, or extend to depths greater than those of normal observation, if the horizons have resulted from pedogenic processes.

B Horizons

B horizons are mineral horizons that typically formed below an A, V, E, or O horizon. They exhibit obliteration of all or much of the original rock structure and show one or more of the following as evidence of pedogenesis:

1. Illuvial concentration of silicate clay, iron, aluminum, humus, sesquioxides, carbonates, gypsum, salts more soluble than gypsum, or silica, alone or in combination;
2. Evidence of the removal, addition, or transformation of carbonates, anhydrite, and/or gypsum;
3. Residual concentration of oxides, sesquioxides, and silicate clay, alone or in combination;
4. Coatings of sesquioxides that make the horizon color conspicuously lower in value, higher in chroma, or redder in hue than overlying and underlying horizons, without apparent illuviation of iron;
5. Alteration that forms silicate clay or liberates oxides, or both, and that forms pedogenic structure if volume changes accompany changes in moisture content;
6. Brittleness; or
7. Strong gleying when accompanied by other evidence of pedogenic change.

All of the different kinds of B horizons are, or originally were, subsurface horizons. B horizons include horizons (cemented or not cemented) with illuvial concentrations of carbonates, gypsum, or silica that are the result of pedogenic processes. They are contiguous to other genetic horizons and brittle layers that show other evidence of alteration, such as prismatic structure or illuvial accumulation of clay.

B horizons do not include layers in which clay films coat rock fragments or cover finely stratified unconsolidated sediments, regardless of whether the films formed in place or by illuviation; layers into which carbonates have been illuviated but that are not contiguous to an overlying genetic horizon; and layers with strong gleying but no other pedogenic changes.

C Horizons or Layers

C horizons or layers are mineral horizons or layers, excluding strongly cemented and harder bedrock, that are little affected by pedogenic processes and lack properties of O, A, V, E, B, and L horizons. Their material may be either like or unlike that from which the solum presumably formed. The C horizon may have been modified, even if there is no evidence of pedogenesis.

Included as C layers (and typically designated Cr) are sediment, saprolite, bedrock, and other geologic materials that are moderately cemented or less cemented (see table 3-7). The excavation difficulty of these materials commonly is low or moderate (see table 3-14). In descriptions of soils that formed in material that is already highly weathered, if this material does not meet the requirements of an A, V, E, or B horizon, it is designated by the letter C. Changes are not considered pedogenic if they are not related to the overlying horizons. Some layers that have accumulations of silica, carbonates, gypsum, or more soluble salts are included in C horizons, even if cemented. However, if a cemented layer formed through pedogenic processes, rather than geologic processes (e.g., lithification), it is considered a B horizon.

R Layers

R layers consist of strongly cemented to indurated bedrock. Granite, basalt, quartzite, limestone, and sandstone are examples of bedrock that commonly is cemented enough to be designated by the letter R. The excavation difficulty of these layers commonly exceeds high. The R layer is sufficiently coherent when moist to make hand-digging with a spade impractical, although it may be chipped or scraped. Some R layers can be ripped with heavy power equipment. The bedrock may have fractures, but these are generally too few or too widely spaced to allow root penetration. The fractures may be coated or filled with clay or other material.

M Layers

M layers are root-limiting layers beneath the soil surface consisting of nearly continuous, horizontally oriented, human-manufactured materials. Examples of materials designated by the letter M include geotextile liners, asphalt, concrete, rubber, and plastic, if they occur as continuous, horizontal layers.

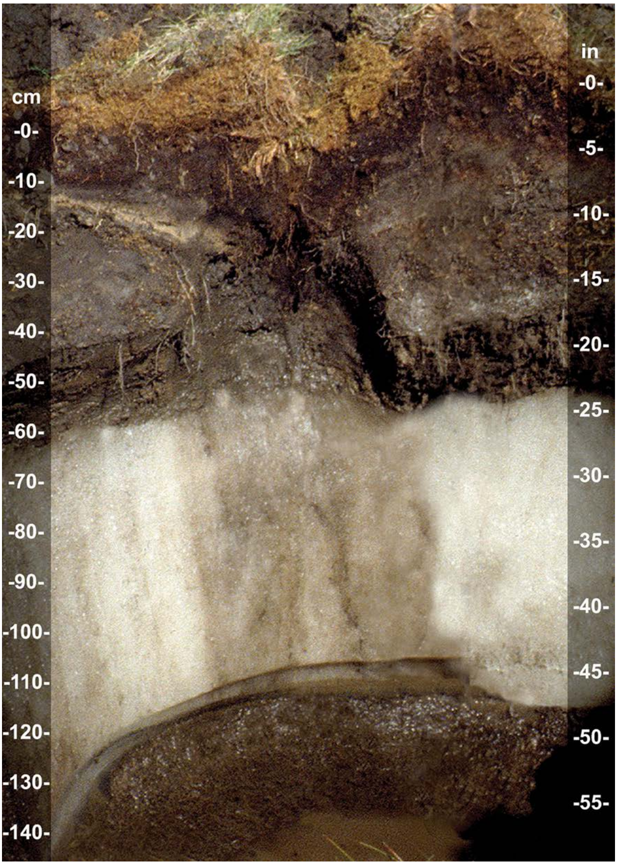
W Layers

W layers are used to identify water layers within or beneath the soil (fig. 3-3). They are not merely layers of saturated soil material but rather zones of water between soil layers. The water layer is designated “Wf” if it is permanently frozen (as in a glacic horizon) and “W” if it is not permanently frozen (as in a floating bog). The designations W and Wf are not used for shallow water, ice, or snow above the soil surface.

Transitional and Combination Horizons

In some cases a single master horizon designation does not adequately convey information about the layer, such as where the horizon transitions

Figure 3-3



A soil (a Glacistel in Alaska) with a permanently frozen ice layer (designated "Wf") between depths of 60 and 130 cm. (Photo courtesy of John Kelley)

to another layer or where it contains distinct parts from two kinds of master horizons.

Transitional Horizons

Transitional horizons are dominated by properties of one master horizon but have subordinate properties of another. They are designated by two capital-letter symbols, e.g., AB, EB, BE, or BC. The first letter indicates the horizon whose properties dominate the transitional horizon. An AB horizon, for example, has characteristics of both an overlying A horizon and an underlying B horizon, but it is more like the A horizon than the B.

In some cases, a horizon can be designated as transitional even if one of the master horizons to which it transitions is not present. For example, a BE horizon recognized in a truncated soil has properties similar to those of a BE horizon in a soil from which the overlying E horizon has not been removed by erosion. A BC horizon may be recognized even if no underlying C horizon is present: it transitions to assumed parent materials.

Combination Horizons

Combination horizons have two distinct parts that have recognizable properties of the two kinds of master horizons. They are designated by two capital-letter symbols (master horizons) separated by a virgule (/), e.g., E/B, B/E, or B/C. Most of the individual parts of one horizon component are surrounded by the other. The designation may be used even when horizons similar to one or both of the components are not present, provided that the separate components can be recognized in the combination horizon. The first letter indicates the horizon with the greater volume.

Because single sets of designators do not cover all situations, some improvising may be necessary. For example, Lamellic Udipsamments have lamellae that are separated from each other by eluvial layers. It is generally not practical to describe each lamella and eluvial layer as a separate horizon, so the horizons can be combined and the components described separately. The horizon with several lamellae and eluvial layers can be designated as an "E and Bt" horizon. The complete horizon sequence for these soils could be: Ap-Bw-E and Bt1-E and Bt2-C.

Suffix Symbols

Lowercase letters are used as suffixes to designate specific subordinate distinctions within master horizons and layers. The term "accumulation," which is used in many of the suffix definitions, indicates that the horizon has more of the material in question than is presumed to have been present in the parent material. The use of a suffix symbol is not restricted only to those horizons that meet certain criteria for diagnostic horizons and other criteria as defined in *Soil Taxonomy*. If there is any evidence of accumulation, a suffix (or suffixes) can be used. The suffix symbols and their meanings follow:

a *Highly decomposed organic material*
This symbol is used with O horizons to indicate the most highly decomposed organic materials, which have a fiber content of less than 17 percent (by volume) after rubbing.

b *Buried genetic horizon*
This symbol indicates identifiable buried horizons with major genetic features that developed before burial. Genetic horizons may or may not have formed in the overlying material, which may be either like or unlike the assumed parent material of the buried horizon. This symbol is not used to separate horizons composed of organic soil material (that are forming at the soil surface) from underlying horizons composed of mineral soil material. It may be used in organic soils, but only if they are buried by mineral soil materials.

c *Concretions or nodules*
This symbol indicates a significant accumulation of concretions or nodules. Cementation is required. The cementing agent commonly is iron, aluminum, manganese, or titanium. It cannot be silica, dolomite, calcite, gypsum, anhydrite, or soluble salts.

co *Coprogenous earth*
This symbol, used only with L horizons, indicates a limnic layer of coprogenous earth (sedimentary peat).

d *Physical root restriction*
This symbol indicates non-cemented, root-restricting layers in naturally occurring or human-made sediments or materials. Examples of natural layers are dense till and some non-cemented shales and siltstones. Examples of human-made dense layers are plowpans and mechanically compacted zones in human-transported material.

di *Diatomaceous earth*
This symbol, used only with L horizons, indicates a limnic layer of diatomaceous earth.

e *Organic material of intermediate decomposition*
This symbol is used with O horizons to indicate organic materials of intermediate decomposition. The fiber content of these materials is 17 to less than 40 percent (by volume) after rubbing.

f *Frozen soil or water*
This symbol indicates that a horizon or layer contains permanent ice. It is not used for seasonally frozen layers or for dry permafrost.

ff *Dry permafrost*
This symbol indicates a horizon or layer that is continually colder than 0 °C and does not contain enough ice to be cemented by ice. It is not used for horizons or layers that have a temperature warmer than 0 °C at some time during the year.

g *Strong gleying*
This symbol indicates either that iron has been reduced and removed during soil formation or that saturation with stagnant water has preserved iron in a reduced state. Most of the affected layers have chroma of 2 or less, and many have redox concentrations. The low chroma can represent either the color of reduced iron or the color of the uncoated sand and silt particles from which iron has been removed. The symbol is not used for soil materials of low chroma that have no history of wetness, such as some shales or E horizons. If it is used with B horizons, pedogenic change (e.g., soil structure) in addition to gleying is implied. If no other pedogenic change besides gleying has taken place, the horizon is designated "Cg."

h *Illuvial accumulation of organic matter*
This symbol is used with B horizons to indicate the accumulation of illuvial, amorphous, dispersible complexes of organic matter and sesquioxides. The sesquioxide component is dominated by aluminum and is present only in very small quantities. The organo-sesquioxide material coats sand and silt particles. In some horizons these coatings have coalesced, filled pores, and cemented the horizon. The symbol *h* is also used in combination with the symbol *s* (e.g., Bhs) if the amount of the sesquioxide component is significant but the value and chroma, moist, of the horizon are 3 or less.

i *Slightly decomposed organic material*
This symbol is used with O horizons to indicate the least decomposed of the organic materials. The fiber content of these materials is 40 percent or more (by volume) after rubbing.

j *Accumulation of jarosite*
This symbol indicates an accumulation of jarosite, which is a potassium (ferric) iron hydroxy sulfate mineral,

$KFe_3(SO_4)_2(OH)_6$. Jarosite is commonly the product of pyrite that has been exposed to an oxidizing environment. It has hue of 2.5Y or yellower and normally has chroma of 6 or more, although chroma as low as 3 or 4 has been reported. It forms in preference to iron (hydr)oxides in active acid sulfate soils at pH of 3.5 or less and can be stable for long periods of time in post-active acid sulfate soils with higher pH.

jj *Evidence of cryoturbation*
This symbol indicates evidence of cryoturbation, which includes irregular and broken horizon boundaries, sorted rock fragments, and organic soil materials occurring as bodies and broken layers within and/or between mineral soil layers. The organic bodies and layers are most commonly at the contact between an active layer and the permafrost.

k *Accumulation of secondary carbonates*
This symbol indicates an accumulation of visible pedogenic calcium carbonate (less than 50 percent, by volume). Carbonate accumulations occur as carbonate filaments, coatings, masses, nodules, disseminated carbonate, or other forms.

kk *Engulfment of horizon by secondary carbonates*
This symbol indicates major accumulations of pedogenic calcium carbonate. It is used when the soil fabric is plugged with fine grained pedogenic carbonate (50 percent or more, by volume) that occurs as an essentially continuous medium. It corresponds to the Stage III (or higher) plugged horizon of the carbonate morphogenetic stages (Gile et al., 1966).

m *Pedogenic cementation*
This symbol indicates continuous or nearly continuous pedogenic cementation. It is used only for horizons that are more than 90 percent cemented but may be fractured. The cemented layer is physically root-restrictive. The predominant cementing agent (or the two dominant ones) can be indicated by letter suffixes, singly or in pairs. The horizon suffix *kkm* (and the less commonly used *km*) indicates cementation by carbonates; *qm*, cementation by silica; *sm*, cementation by iron; *yym*, cementation by gypsum; *kqm*, cementation by carbonates and silica; and *zm*, cementation

by salts more soluble than gypsum. The symbol *m* is not used for permanently frozen layers impregnated by ice.

ma *Marl*
This symbol, used only with L horizons, indicates a limnic layer of marl.

n *Accumulation of sodium*
This symbol indicates an accumulation of exchangeable sodium.

o *Residual accumulation of sesquioxides*
This symbol indicates a residual accumulation of sesquioxides.

p *Tillage or other disturbance*
This symbol indicates disturbance of a horizon by mechanical means, pasturing, or similar uses. A disturbed organic horizon is designated "Op." A disturbed mineral horizon is designated "Ap" even if it is clearly a former E, B, or C horizon.

q *Accumulation of silica*
This symbol indicates an accumulation of secondary silica.

r *Weathered or soft bedrock*
This symbol is used with C horizons to indicate layers of bedrock that are moderately cemented or less cemented. Examples are weathered igneous rock and partly consolidated sandstone, siltstone, or shale. The excavation difficulty is low to high.

s *Illuvial accumulation of sesquioxides and organic matter*
This symbol is used with B horizons to indicate an accumulation of illuvial, amorphous, dispersible complexes of organic matter and sesquioxides, if both the organic matter and sesquioxide components are significant and if either the value or chroma, moist, of the horizon is 4 or more. The symbol is also used in combination with *h* (e.g., Bhs) if both the organic matter and sesquioxide components are significant and if the value and chroma, moist, are 3 or less.

se *Presence of sulfides*
This symbol indicates the presence of sulfides in mineral or organic horizons. Horizons with sulfides typically have dark

colors (e.g., value of 4 or less, chroma of 2 or less). These horizons typically form in soils associated with coastal environments that are permanently saturated or submerged (i.e., tidal marshes or estuaries). Soil materials which have sulfidization actively occurring emanate hydrogen sulfide gas, which is detectable by its odor (Fanning and Fanning, 1989; Fanning et al., 2002). Sulfides may also occur in upland environments that have a source of sulfur. Soils in such environments are commonly of geologic origin and may not have a hydrogen sulfide odor. Examples include soils that formed in parent materials derived from coal deposits, such as lignite, or soils that formed in coastal plain deposits, such as glauconite, that have not been oxidized because of thick layers of overburden.

ss *Presence of slickensides*
This symbol indicates the presence of pedogenic slickensides. Slickensides result directly from the swelling of clay minerals and shear failure, commonly at angles of 20 to 60 degrees above horizontal. They are indicators that other vertic characteristics, such as wedge-shaped peds and surface cracks, may be present.

t *Accumulation of silicate clay*
This symbol indicates an accumulation of silicate clay that either has formed within a horizon and subsequently has been translocated within the horizon or that has been moved into the horizon by illuviation, or both. At least some part of the horizon shows evidence of clay accumulation, either as coatings on surfaces of peds or in pores, as lamellae, or as bridges between mineral grains.

u *Presence of human-manufactured materials (artifacts)*
This symbol indicates the presence of objects or materials that have been created or modified by humans, typically for a practical purpose in habitation, manufacturing, excavation, or construction activities. Examples of artifacts are bitumen (asphalt), boiler slag, bottom ash, brick, cardboard, carpet, cloth, coal combustion by-products, concrete (detached pieces), debitage (i.e., stone tool flakes), fly ash, glass, metal, paper, plasterboard, plastic, potsherd, rubber, treated wood, and untreated wood products.

v *Plinthite*
This symbol is used to indicate the presence of iron-rich, humus-poor, reddish material that is firm or very firm when moist and is less than strongly cemented. Plinthite hardens irreversibly when exposed to the atmosphere and to repeated wetting and drying.

w *Development of color or structure*
This symbol is used only with B horizons to indicate the development of color or structure, or both, with little or no apparent illuvial accumulation of material. Note: It is not used to indicate a transitional horizon.

x *Fragipan character*
This symbol indicates a genetically developed layer that has a combination of firmness and brittleness and commonly a higher bulk density than adjacent layers. Some part of the layer is physically root-restrictive.

y *Accumulation of gypsum*
This symbol indicates an accumulation of gypsum. It is used when the horizon fabric is dominated by soil particles or minerals other than gypsum. Gypsum is present in amounts that do not significantly obscure or disrupt other features of the horizon. This symbol is also used to indicate the presence of anhydrite.

yy *Dominance of horizon by gypsum*
This symbol indicates a horizon that is dominated by the presence of gypsum. The gypsum content may be due to an accumulation of secondary gypsum, the transformation of primary gypsum inherited from parent material, or other processes. This symbol is used when the horizon fabric has such an abundance of gypsum (generally 50 percent or more, by volume) that pedogenic and/or lithologic features are obscured or disrupted by growth of gypsum crystals. Horizons that have this suffix typically are highly whitened (e.g., value of 7 through 9.5 and chroma of 4 or less). This symbol is also used to connote the presence of anhydrite.

z *Accumulation of salts more soluble than gypsum*
This symbol indicates an accumulation of salts that are more soluble than gypsum.

Conventions for Using Horizon Designation Symbols

The following guidelines can be used in assigning horizon designation symbols to soil horizons and layers.

Letter Suffixes

Many master horizons and layers that are symbolized by a single capital letter can have one or more lowercase-letter suffixes. The following rules apply:

1. Letter suffixes directly follow the capital letter of the master horizon or layer, or the prime symbol, if used.
2. More than three suffixes are rarely used.
3. If more than one suffix is needed, the following letters (if used) are written first: *a, d, e, h, i, r, s, t,* and *w*. None of these letters are used in combination for a single horizon, except to designate a Bhs horizon or Crt layer.
4. If more than one suffix is needed and the horizon is not buried, the following symbols, if used, are written last: *c, f, g, m, v,* and *x*. Examples are Bjc and Bkkm. If any of these suffixes are used together in the same horizon, symbols *c* and *g* are written last (e.g., Btvg), with one exception. If the symbol *f* (frozen soil or water) is used together with any of the other symbols in this rule, it is written last, e.g., Cdgf.
5. If a genetic horizon is buried, the suffix *b* is written last, e.g., Oab.
6. Suffix symbols *h, s,* and *w* are not used with *g, k, kk, n, o, q, y, yy,* or *z*.
7. If the above rules do not apply to certain suffixes, such as *k, kk, q, y,* or *yy,* the suffixes may be listed together in order of assumed dominance or alphabetically if dominance is not a concern.

A B horizon that has a significant accumulation of clay and also shows development of color or structure, or both, is designated "Bt" (suffix symbol *t* has precedence over symbols *w, s,* and *h*). A B horizon that is gleyed or that has accumulations of carbonates, sodium, silica, gypsum, salts more soluble than gypsum, or residual accumulations of sesquioxides carries the appropriate symbol: *g, k, kk, n, q, y, yy, z,* or *o*. If illuvial clay is also present, the symbol *t* precedes the other symbol, e.g., Bto.

Vertical Subdivisions

Commonly, a horizon or layer designated by a single letter or a combination of letters has to be subdivided. For this purpose, numbers are added to the letters of the horizon designation. These numbers follow all the letters. Within a sequence of C horizons, for example, successive layers may be designated C1, C2, C3, etc. If the lower horizons are strongly gleyed and the upper horizons are not strongly gleyed, they may be designated C1-C2-Cg1-Cg2 or C-Cg1-Cg2-R.

These conventions apply regardless of the purpose of the subdivision. In many soils a horizon that could be identified by a single set of letters is subdivided to recognize differences in morphological features, such as structure, color, or texture. These divisions are numbered consecutively, but the numbering starts again at 1 when any letter of the horizon symbol changes, e.g., Bt1-Bt2-Btk1-Btk2 (not Bt1-Bt2-Btk3-Btk4). The numbering of vertical subdivisions within consecutive horizons is not interrupted at a discontinuity (indicated by a numerical prefix) if the same letter combination is used in both materials, e.g., Bs1-Bs2-2Bs3-2Bs4 (not Bs1-Bs2-2Bs1-2Bs2).

During sampling for laboratory analyses, thick soil horizons are sometimes subdivided even though differences in morphology are not evident in the field. These subdivisions are identified by numbers that follow the respective horizon designations. For example, four subdivisions of a Bt horizon sampled by 10-cm increments are designated Bt1, Bt2, Bt3, and Bt4. If the horizon has already been subdivided because of differences in morphological features, the set of numbers that identifies the additional sampling subdivisions follows the first number. For example, three subdivisions of a Bt2 horizon sampled by 10-cm increments are designated Bt21, Bt22, and Bt23. The descriptions for each of these sampling subdivisions can be the same, and a statement indicating that the horizon has been subdivided only for sampling purposes can be added.

Discontinuities

Numbers are used as prefixes to horizon designations (specifically, A, V, E, B, C, and R) to indicate discontinuities in mineral soils. These prefixes are distinct from the numbers that are used as suffixes denoting vertical subdivisions.

A discontinuity that can be identified by a number prefix is a significant change in particle-size distribution or mineralogy that indicates a difference in the parent material from which the horizons have formed and/or a significant difference in age, unless the difference in age is indicated by the suffix *b*. Symbols that identify discontinuities are used only when they can contribute substantially to an understanding of the relationships among horizons. The stratification common to soils that formed in alluvium is not designated as a discontinuity, unless particle-size distribution differs markedly from layer to layer (i.e., particle-size classes are strongly contrasting) even though genetic horizons may have formed in the contrasting layers.

If a soil formed entirely in one kind of material, the whole profile is understood to be material 1 and the number prefix is omitted from the symbol. Similarly, the uppermost material in a profile consisting of two or more contrasting materials is understood to be material 1 and the number is omitted. Numbering starts with the second layer of contrasting material, which is designated 2. Underlying contrasting layers are numbered consecutively. Even when the material of a layer below material 2 is similar to material 1, it is designated 3 in the sequence; the numbers indicate a change in materials, not types of material. Where two or more consecutive horizons have formed in the same kind of material, the same prefix number indicating the discontinuity is applied to all the designations of horizons in that material, for example, Ap-E-Bt1-2Bt2-2Bt3-2BC. The suffix numbers designating vertical subdivisions of the Bt horizon continue in consecutive order across the discontinuity. However, vertical subdivisions do not continue across lithologic discontinuities if the horizons are not consecutive or contiguous to each other. If other horizons intervene, another vertical numbering sequence begins for the lower horizons, for example, A-C1-C2-2Bw1-2Bw2-2C1-2C2.

If an R layer is below a soil that formed in residuum and if it is similar to the material from which the soil developed, the number prefix is not used. The prefix is used, however, if it is thought that the R layer would weather to material unlike that in the solum, e.g., A-Bt-C-2R or A-Bt-2R. If part of the solum has formed in residuum, the symbol R is given the appropriate prefix, for example, Ap-Bt1-2Bt2-2Bt3-2C1-2C2-2R.

A buried genetic horizon (designated by the suffix *b*) requires special consideration. It is obviously not in the same deposit as the overlying horizons. Some buried horizons, however, formed in material that is lithologically like the overlying deposit. In this case, a prefix is not used to distinguish material of the buried horizon. If the material in which a horizon of a buried soil formed is lithologically unlike the overlying material, the discontinuity is indicated by a number prefix and the symbol for the buried horizon also is used, for example, Ap-Bt1-Bt2-BC-C-2ABb-2Btb1-2Btb2-2C.

Discontinuities between different kinds of layers in organic soils are not identified. In most cases, such differences are identified by letter suffixes if the different layers are organic materials (e.g., Oe vs. Oa) or by the master horizon symbol if the different layers are mineral or limnic materials (e.g., Oa vs. Ldi).

The Prime Symbol

If two or more horizons with identical number prefixes and letter combinations are separated by one or more horizons with a different horizon designation, identical letter and number symbols can be used for those horizons with the same characteristics. For example, the sequence A-E-Bt-E-Btx-C identifies a soil that has two E horizons. To emphasize this characteristic, the prime symbol (´) is added after the symbol of the lower of the two horizons that have identical designations, e.g., A-E-Bt-E´-Btx-C. The prime symbol is placed after the master horizon symbol and before the suffix letter symbol or symbols (if used), for example, B´t.

The prime symbol is not used unless all letter and number prefixes are completely identical. The sequence A-Bt1-Bt2-2E-2Bt1-2Bt2 is an example. Because it has two Bt master horizons of different lithologies, the Bt horizons are not identical and the prime symbol is not needed. The prime symbol is used for soils with lithologic discontinuities if horizons have identical designations. For example, a soil with the sequence A-C-2Bw-2Bc-2B´w-3Bc has two identical 2Bw horizons but two different Bc horizons (2Bc and 3Bc); the prime symbol is used only with the lower 2Bw horizon (2B´w). In the rare cases where three layers have identical letter symbols, double prime symbols can be used for the lowest of these horizons, for example, E´´.

Vertical subdivisions of horizons or layers (number suffixes) are not taken into account when the prime symbol is assigned. The sequence A-E-Bt-E´-B´t1-B´t2-B´t3-C is an example.

These same principles apply in designating layers of organic soils. The prime symbol is used only to distinguish two or more horizons that have identical symbols. For example, Oi-C-O´i-C´ indicates a soil with two identical Oi and C layers and Oi-C-Oe-C´ indicates a soil with two identical C layers. The prime symbol is added to the lower layers to differentiate them from the upper layers.

The Caret Symbol

The caret symbol (^) is used as a prefix to indicate horizons and layers that formed in human-transported material. This material has been moved horizontally onto a pedon from a source area outside of that pedon by purposeful human activity, usually with the aid of machinery or hand tools. Number prefixes may be used before the caret symbol to indicate the presence of discontinuities within the human-transported material (e.g., ^Au-^Bwu-^BCu-2^Cu1-2^Cu2) or between the human-transported material and underlying horizons formed in other parent materials (e.g., ^A-^C1-2^C2-3Bwb).

Sample Horizons and Sequences

The following examples illustrate some common horizon and layer sequences of important soils (subgroup taxa) and the use of numbers to identify vertical subdivisions and discontinuities. Transitional horizons, combination horizons, and the use of the prime and caret symbols are also illustrated.

Mineral Soils

Typic Hapludoll: A1-A2-Bw-BC-C
Typic Haplustoll: Ap-A-Bw-Bk-Bky1-Bky2-C
Cumulic Haploxeroll: Ap-A-Ab-C-2C-3C
Typic Argialboll: Ap-A-E-Bt1-Bt2-BC-C
Typic Argiaquoll: A-AB-BA-Btg-BCg-Cg
Alfic Udivitrand: Oi-A-Bw1-Bw2-2E/Bt-2Bt/E1-2Bt/E2-2Btx1-2Btx2
Entic Haplorthod: Oi-Oa-E-Bs1-Bs2-BC-C
Typic Haplorthod: Ap-E-Bhs-Bs-BC-C1-C2
Typic Fragiudalf: Oi-A-E-BE-Bt1-Bt2-B/E-Btx1-Btx2-C
Typic Haploxeralf: A1-A2-BAt-2Bt1-2Bt2-2Bt3-2BC-2C
Glossic Hapludalf: Ap-E-B/E-Bt1-Bt2-C
Typic Paleudult: A-E-Bt1-Bt2-B/E-B´t1-B´t2-B´t3
Typic Hapludult: Oi-A1-A2-BA-Bt1-Bt2-BC-C
Arenic Plinthic Paleudult: Ap-E-Bt-Btc-Btv1-Btv2-BC-C
Xeric Haplodurid: A-Bw-Bkq-2Bkqm
Vertic Natrigypsid: A-Btn-Btkn-Bky-2By-2BCy-2Cr
Typic Calciargid: A-Bt-Btk1-Btk2-C
Typic Dystrudept: Ap-Bw1-Bw2-C-R
Typic Fragiudept: Ap-Bw-E-Bx1-Bx2-C
Typic Endoaquept: Ap-AB-Bg1-Bg2-BCg-Cg
Typic Haplustert: Ap-A-Bss-BCss-C
Typic Hapludox: Ap-A/B-Bo1-Bo2-Bo3-Bo4-Bo5
Typic Udifluvent: Ap-C-Ab-C´
Glacic Histoturbel: Oi-OA-Bjjg-Wf-Cgf

Organic Soils

Typic Haplosaprist: Oap-Oa1-Oa2-Oa3-C
Typic Sphagnofibrist: Oi1-Oi2-Oi3-Oe
Limnic Haplofibrist: Oi-Lco-O´i1-O´i2-L´co-Oe-C
Lithic Cryofolist: Oi-Oa-R
Typic Hemistel: Oi-Oe-Oef

Human-Altered Soils

Anthrodensic Ustorthent: ^Ap-^C/B-^Cd-2C
Anthroportic Udorthent: ^Ap-^Cu-Ab-Btb-C

Subaqueous Soils

Psammentic Frasiwassents: A1-A2-CA-Cg1-Cg2-Cg3-Cg4
Thapto-Histic Sulfiwassents: Ase-Cse1-Cse2-Oase1-Oa1-Oa2
Sulfic Psammowassents: A-Cg1-Cg2-Aseb-C´g-A´seb-C´´g1-C´´g2-C´´g3

Cyclic and Intermittent Horizons and Layers

Soils with cyclic or intermittent horizons pose special challenges in describing soil profiles. The profile of a soil having cyclic horizons exposes layers whose boundaries are near the surface at one point and extend deep into the soil at another. The aggregate horizon thickness may be only 50 cm at one place but more than 125 cm at a place 2 meters away. The cycle repeats. It commonly has considerable variation in both depth and horizontal interval but still has some degree of regularity. When the soil is visualized in three dimensions instead of two, some cyclic horizons extend downward in inverted cones. The cone of the lower horizon fits around the cone of the horizon above. Other cyclic horizons appear wedge-shaped.

The profile of a soil having an intermittent horizon shows that the horizon extends horizontally for some distance, ends, and reappears again some distance away. For example, the horizons of Turbels, which by definition are subject to cryoturbation, are irregular, intermittent, and distorted. A B horizon interrupted at intervals by upward extensions of bedrock into the A horizon is another example. The distance between places where the horizon is absent is commonly variable but has some degree of regularity. It ranges from less than 1 meter to several meters.

For soils with cyclic or intermittent horizons or layers, a soil profile at one place may be unlike a profile only a few meters away. Standardized horizon nomenclature and pedon description forms are not well suited to soil profiles with such variability. When describing these types of soils, it is important to make notes on the individual horizons to record the nature of the variations. Photographs and diagrams can also be used to convey the information. Descriptions of the order of horizontal variation as well as vertical variation within a pedon include the kind of variation, the spacing of cycles or interruptions, and the amplitude of depth variation of cyclic horizons.

Boundaries of Horizons and Layers

A boundary is a relatively sharp plane-like division or a more gradual transitional layer between two adjoining horizons or layers. Most boundaries are zones of transition rather than sharp lines of division. Boundaries vary in distinctness and topography.

Distinctness

Distinctness refers to the thickness of the zone within which the boundary can be located. The distinctness of a boundary depends partly on the degree of contrast between the adjacent layers and partly on the thickness of the transitional zone between them. Distinctness is defined in terms of thickness of the transitional zone as follows:

Very abrupt .... less than 0.5 cm
Abrupt.................... 0.5 to less than 2 cm
Clear .... 2 to less than 5 cm
Gradual .... 5 to less than 15 cm
Diffuse .... 15 cm or more

Very abrupt boundaries occur at some lithologic discontinuities, such as geogenic deposits or strata (tephras, alluvial strata, etc.). They can also occur at the contacts of root-limiting layers. Examples are duripans; fragipans; petrocalcic, petrogypsic, and placic horizons; continuous ortstein; and densic, lithic, paralithic, and petroferric contacts. See *Soil Taxonomy* (Soil Survey Staff, 1999) for more information and definitions.

Abrupt soil boundaries, such as those between the E and Bt horizons of many soils, are easily determined. Some boundaries are not readily seen but can be located by testing the soil above and below the boundary. Diffuse boundaries, such as those in many old soils in tropical areas, are very difficult to locate. They require time-consuming comparisons of small specimens of soil from various parts of the profile to determine the midpoint of the transitional zone. For soils that have nearly uniform properties or that change very gradually as depth increases, horizon boundaries are imposed more or less arbitrarily without clear evidence of differences.

Topography

Topography refers to the irregularities of the surface that divides the horizons (fig. 3-4). Terms for topography describe the shape of the contact between horizons as seen in a vertical cross-section. Even though soil layers are commonly seen in vertical section, they are three-dimensional. Terms describing topography of boundaries are:

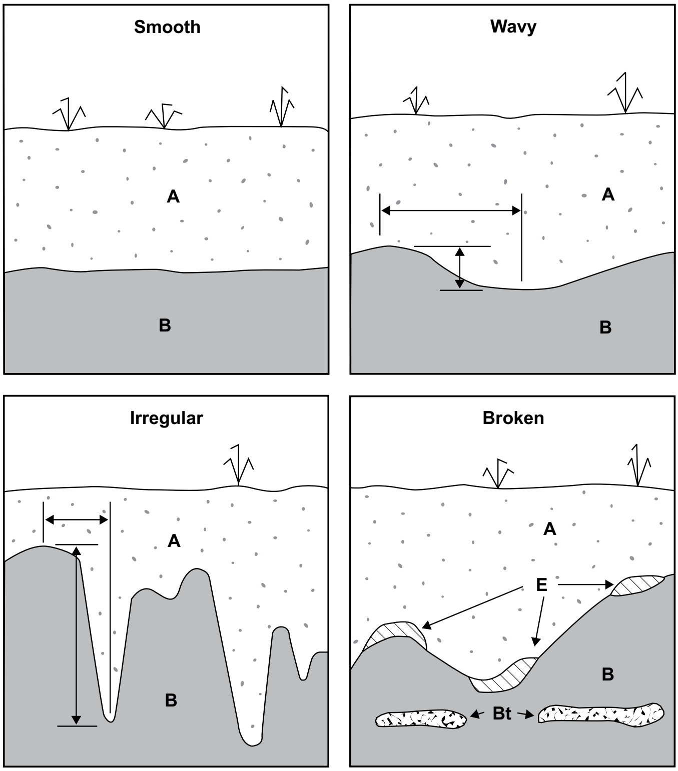
Smooth.—The boundary is a plane with few or no irregularities.

Wavy.—The boundary has undulations in which depressions are wider than they are deep.

Irregular.—The boundary has pockets that are deeper than they are wide.

Broken.—One or both of the horizons or layers separated by the boundary are discontinuous and the boundary is interrupted.

Figure 3-4



Examples of topography classes for horizon boundaries (adapted from Schoeneberger et al., 2012).

Thickness

The thickness of the horizon or layer is recorded by entering depths for the upper and lower boundaries. For horizons or layers with significant lateral variation in thickness, the average horizon thickness may also be noted.

Near Surface Subzones

Background Information

In many soils, the morphology of the uppermost few centimeters (generally from less than 1 to about 18 cm) is strongly controlled by antecedent weather and by soil use. A soil may be freshly tilled and have a loose surface one day and have a strong crust because of a heavy rain the next day. A soil may be highly compacted by livestock and have a firm near surface in one place but have little disturbance to the uppermost few centimeters and be very friable in most other places. These affected soils properties are referred to as "use-dependent" or "dynamic." See chapter 9 for information about studying dynamic soil properties in the field.

The following discussion provides a set of terms for describing subzones of the near surface and, in particular, the near surface of tilled soils. The horizon designations or symbols for describing these near surface subzones are limited. The suffix *d* is used for root-restrictive compacted layers; master horizon symbol *V* may be used to designate some layers with a dominance of vesicular pores. Surface horizons can be subdivided using standard horizon designations to record the subzones. An example horizon sequence could include Ap1 (a mechanically bulked subzone), Ap2 (a water-compacted subzone), and Bd (a mechanically compacted subzone). Descriptions of these separations should also identify the kind of subzone described. Very thin surface crusts (less than about 1 cm thick) are generally described as a special surface feature rather than as a separate layer.

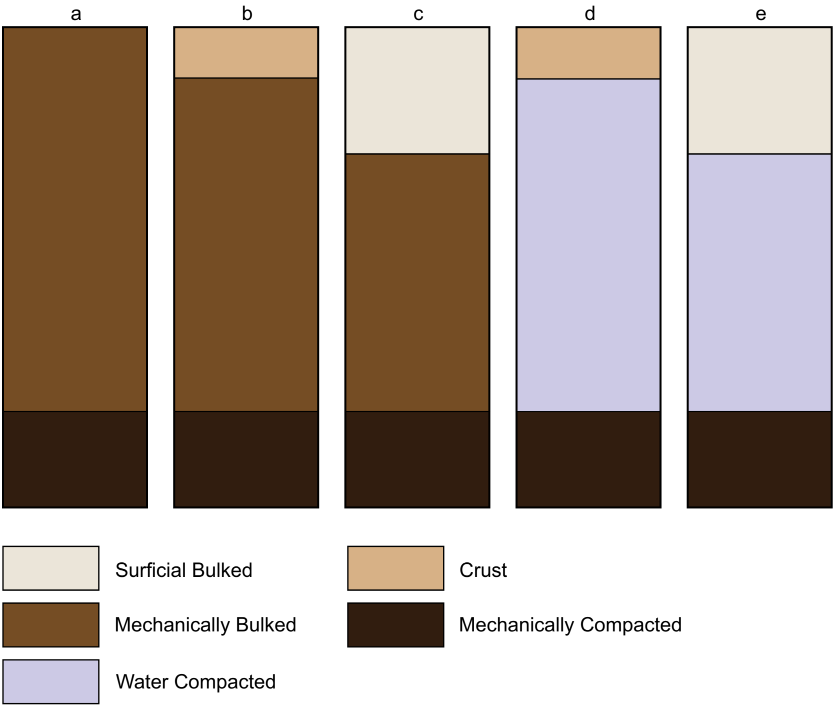
Kinds of Near Surface Subzones

In this section, five kinds of near surface subzones are presented and the general processes leading to their formation are described. The five kinds of subzones are: *mechanically bulked*, *mechanically compacted*, *water compacted*, *surficial bulked*, and *crust* (either biological or chemical). Figure 3-5 shows stylized profiles depicting various combinations of these subzones.

Identification of subzones is not clear cut. Morphological expression of bulking and compaction may be quite different among soils depending on particle-size distribution, organic matter content, clay mineralogy, water regime, or other factors.

The distinction between a bulked and compacted state for soil material with appreciable shrink-swell potential is partly based on the

Figure 3-5



Five kinds of near surface subzones (scale is approximately 18 cm).

potential for the transmission of strain on drying over distances greater than the horizontal dimensions of the larger structural units. In a bulked subzone, little or no strain is propagated; in a compacted subzone, the strain is propagated over distances greater than the horizontal dimensions of the larger structural units. Many soils have low shrink-swell potential because of texture, clay mineralogy, or both. For these soils, the expression of cracks cannot be used to distinguish between a bulked state and a compacted state.

The distinction between compaction and bulking is subjective. It is useful to establish a concept of a normal degree of compaction of the near surface and then compare the actual degree of compaction to this. The concept for tilled soils should be the compaction of soil material on level or convex parts of the tillage-determined relief. The soil should have been subject to the bulking action of conventional tillage without the subsequent mechanical compaction. The subzone in question should have been brought to a *wet* or *very moist* water state from an appreciably drier condition and then dried to *slightly moist* or drier at least once. It should not have been subject, however, to a large number of wetting and drying cycles where the maximum wetness involved the presence of free water. If the soil material has a degree of compaction similar to what would be expected, then the term *normal compaction* is used.

Mechanically Bulked Subzone

The mechanically bulked subzone has undergone, through mechanical manipulation, a reduction in bulk density and an increase in discreteness of structural units, if present. The mechanical manipulation is commonly due to tillage operations. Rupture resistance of the mass overall, inclusive of a number of structural units, is typically *loose* or *very friable* and is occasionally *friable*. Individual structural units may be *friable* or even *firm*. Mechanical continuity among structural units is low. Structure grade, if the soil material exhibits structural units less than 20 mm across, is moderate or strong. Strain that results from contraction on drying of individual structural units may not extend across the structural units. Hence, internally initiated desiccation cracks may be weak or absent even though the soil material in a consolidated condition has considerable shrink-swell potential. Cracks may be present, however, if they initiate deeper in the soil. The mechanically bulked subzone is depicted in figure 3-5 as the first layer in profile a and the second layer in profiles b and c.

Mechanically Compacted Subzone

The mechanically compacted subzone has been subject to compaction, usually due to tillage operations but also by animals. Commonly, mechanical continuity of the fabric and bulk density are increased. Rupture resistance depends on texture and degree of compaction. Generally, *friable* is the minimum class. Mechanical continuity of the fabric permits propagation of strain (that results on drying) only over several centimeters. Internally initiated cracks appear if the soil material has appreciable shrink-swell potential and drying was sufficient. In some soils this subzone restricts root growth. The suffix *d* may be used if compaction results in a strong plow pan. The mechanically compacted subzone is the lowest layer of all profiles shown in figure 3-5.

Water-Compacted Subzone

The water-compacted subzone has been compacted by repetitive large changes in water state without mechanical load, except for the weight of the soil. Repetitive occurrence of free water is particularly conducive to compaction. Depending on texture, moist rupture resistance ranges from *very friable* through *firm*. Structural units, if present, are less discrete than those in the same soil material if mechanically bulked. The subzone generally has weak structure or is massive. Mechanical continuity of the fabric is sufficient for strain that originates on drying to propagate appreciable distances. As a consequence, if shrink-swell potential is sufficient, cracks develop on drying. In many soils, the water-compacted subzone replaces the mechanically bulked subzone over time. The replacement can occur in a single year if the subzone is subject to periodic occurrence of free water with intervening periods of being *slightly moist* or *dry*. The presence of a water-compacted subzone and the absence of a mechanically bulked subzone is an important consequence of no-till farming systems. The water-compacted subzone is depicted in figure 3-5 as the second layer of profiles d and e.

Surficial Bulked Subzone

The surficial bulked subzone occurs in the very near surface. Continuity of the fabric is low. Cracks are not initiated in this subzone but may be present (they may initiate in underlying, more compacted soil). The subzone forms by various processes. Frost action under conditions where the soil is drier than *wet* is one process. Pronounced shrinking and swelling in response to drying and wetting (which is characteristic of Vertisols) is another process. The surficial bulked subzone is depicted in figure 3-5 as the first layer of profiles c and e.

Crust

A crust is a surficial subzone, typically less than 50 mm thick but ranging to as much as 100 mm thick, that exhibits markedly more mechanical continuity of the soil fabric than the zone immediately beneath. Commonly, the original soil fabric has been reconstituted by water action and the original structure has been replaced by a massive condition. While the material is *wet*, raindrop impact (including sprinkler irrigation) and freeze-thaw cycles can lead to reconstitution. The crust is depicted in figure 3-5 as the first layer of profiles b and d.

Crusts may be described in terms of thickness in millimeters, structure and other aspects of the fabric, and consistence, including rupture resistance while dry and micropenetration resistance while wet. Thickness pertains to the zone where reconstitution of the fabric has been pronounced. The distance between surface-initiated cracks (described later in this chapter) may be a useful observation for seedling emergence considerations. If the distance is short, the weight of the crust slabs is low.

Soil material with little apparent reconstitution commonly adheres beneath the crust and is removed with the crust. This soil material, which shows little or no reconstitution, is not part of the crust and does not contribute to the thickness.

Recognized types of soil crusts include biological, chemical and structural.

Biological crusts, which consist of algae, lichens, or mosses, occur on the surface of some soils, especially in some relatively undisturbed settings, such as rangelands. These crusts are easily diminished or destroyed by disturbance.

Chemical crusts commonly occur in arid environments where salty evaporites accumulate at the surface. They include crusts consisting of mineral grains cemented by salts.

Structural crusts form from local transport and deposition of soil material, commonly in tilled fields. They have weaker mechanical continuity than other crusts. The rupture resistance is lower, and the reduction in infiltration may be less than that of crusts with similar texture. Raindrop impact and freeze-thaw cycles contribute to the formation of structural crusts.

Root-Restricting Depth

The root-restricting depth is the depth at which physical (including soil temperature) and/or chemical characteristics strongly inhibit root penetration. Restriction means the incapability to support more than a few *fine* or *very fine* roots if the depth from the soil surface and the water state (other than the occurrence of frozen water) are not limiting. For cotton, soybeans, and other crops that have less abundant roots than grasses have, the *very few* class is used instead of the *few* class. The restriction may be below where plant roots normally occur because of limitations in water state, temperatures, or depth from the surface. The root-restricting depth should be evaluated for the specific plants important to the use of the soil. These plants are indicated in the soil description. The root-restriction depth may differ depending on the plant.

Morphology and Root Restriction

Root-depth observations should be used to make the generalization of root-restricting depth. If these are not available (commonly because roots do not extend to the depth of concern) then inferences may be made from morphology. A change in particle-size distribution alone (e.g., loamy sand over gravel) is not typically a basis for physical root restriction. Some guidelines for inferring physical restriction are given below. Chemical restrictions, such as high levels of extractable aluminum and/or low levels of extractable calcium, are not considered; these are generally not determinable by field examination alone.

Physical root restriction is assumed:

1. At the contact with bedrock and other continuously cemented materials, regardless of the rupture resistance class or thickness;
2. For certain horizons or layers, such as *fragipans* or those consisting of *densic materials*, that, although non-cemented, are root restrictive by definition; and
3. For layers with a combination of structure, consistence, and/or penetration resistance that suggests that the resistance of the soil fabric to root entry is high and that vertical cracks and planes of weakness for root entry are absent or widely spaced (i.e., more than 10 cm apart) as follows:
    a. For a zone more than 10 cm thick that when *very moist* or *wet* is *very firm* (*firm*, if sandy) or firmer or that has a penetration resistance class of *large* (i.e., *high* or higher), and is *massive* or *platy* or has *weak* structure of any type.
    b. For a zone that has structural units of any grade with a vertical repeat distance of more than 10 cm and while *very moist* or *wet* is *very firm* (*firm*, if sandy) or *extremely firm*, or has a *large* (i.e., *high* or higher) penetration resistance.

Classes of Root-Restricting Depth

Terms describing depth to physical restriction for roots are:

Very shallow .... less than 25 cm
Shallow.................. 25 to less than 50 cm
Moderately deep .... 50 to less than 100 cm
Deep....................... 100 to less than 150 cm
Very deep............... 150 cm or more

Particle-Size Distribution

This section discusses particle-size distribution of mineral soil separates. *Fine earth* indicates particles smaller than 2 mm in diameter. Fragments 2 mm or larger consist of *rock fragments,* pieces of geologic or pedogenic material with a strongly cemented or more cemented rupture-resistance class; *pararock fragments,* pieces of geologic or pedogenic material with an extremely weakly cemented to moderately cemented rupture-resistance class; and *discrete artifacts,* pieces of human-manufactured material. Particle-size distribution of fine earth is determined in the field mainly by feel. The content of rock fragments, pararock fragments, and discrete artifacts is an estimate of the proportion of the soil volume that they occupy.

Soil Separates

After pretreatment to remove organic matter, carbonates, soluble salts, and other cementing agents and after dispersion to physically separate individual soil particles, the U.S. Department of Agriculture uses the following size separates for fine-earth fraction:

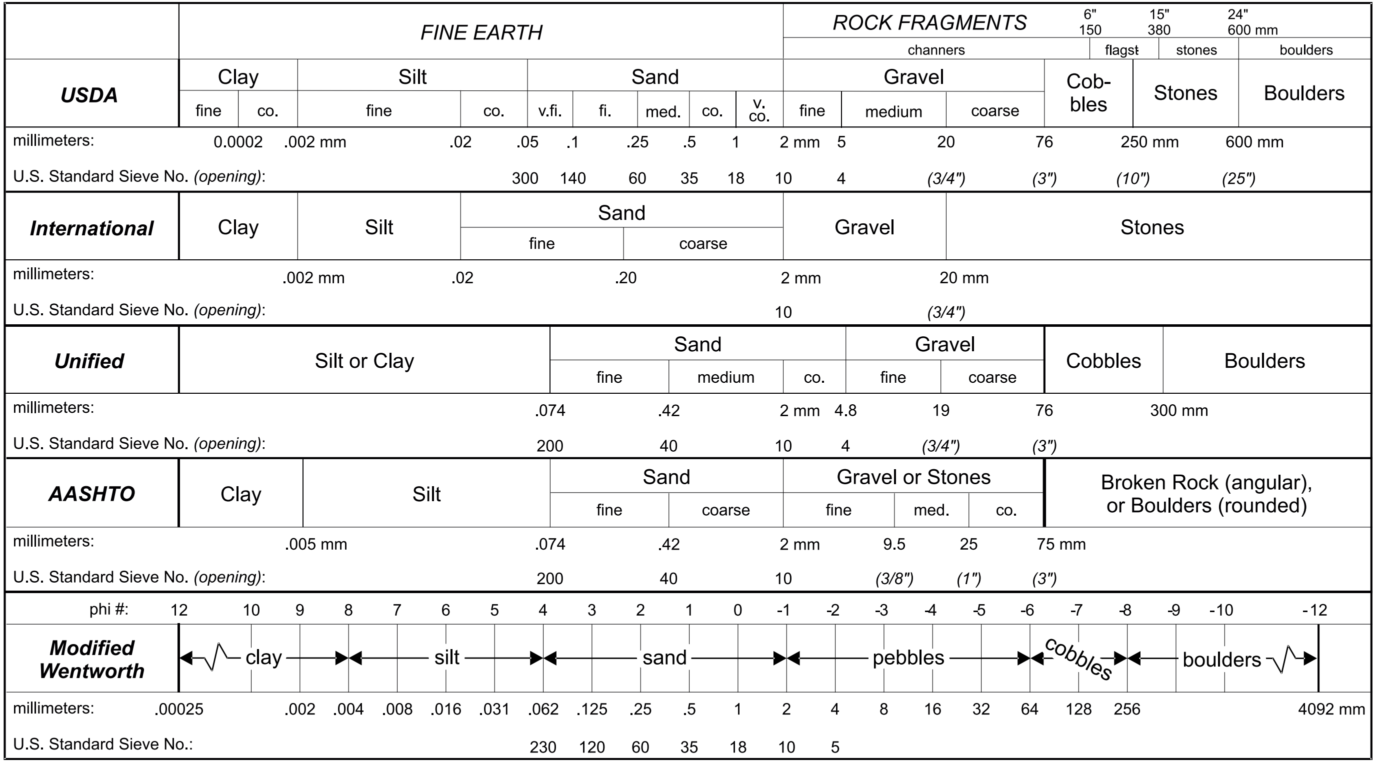
Very coarse sand.... < 2.0 to > 1.0 mm
Coarse sand............ 1.0 to > 0.5 mm
Medium sand......... 0.5 to > 0.25 mm
Fine sand................ 0.25 to > 0.10 mm
Very fine sand........ 0.10 to > 0.05 mm
Coarse silt.............. 0.05 to > 0.02 mm
Fine silt.................. 0.02 to > 0.002 mm
Coarse clay............ 0.002 to > 0.0002 mm
Fine clay................ less than or equal to 0.0002 mm

Figure 3-6 compares the USDA system for naming various sizes of soil separates with four other systems: International (Soil Survey Staff, 1951); Unified (ASTM, 2011); AASHTO (AASHTO, 1997a, 1997b); and Modified Wentworth (Ingram, 1982).

Soil Texture

Soil texture refers to the weight proportion of the separates for particles less than 2 mm in diameter as determined from a laboratory particle-size distribution. The pipette method is the preferred standard, but the hydrometer method also is used in field labs (Soil Survey Staff, 2009). If used, the hydrometer method should be noted with the results.

Field estimates of soil texture class are based on qualitative criteria, such as how the soil feels (gritty, smooth, sticky) and how it responds to rubbing between the fingers to form a ribbon. Estimated field texture class should be checked against laboratory determinations, and the field criteria used to estimate texture class should be adjusted as necessary to reflect local conditions. Sand particles feel gritty and can be seen individually with the naked eye. Silt particles have a smooth feel to the fingers when



Relationships among particle-size classes of the USDA system and four other systems.

dry or wet and cannot be seen individually without magnification. Clay soils are sticky in some areas and not sticky in others. For example, soils dominated by smectitic clays feel different from soils that contain similar amounts of micaceous or kaolinitic clay. The relationships that are useful for judging texture of one kind of soil may not apply as well to another kind.

Some soils are not dispersed completely in the standard laboratory particle-size analysis. Examples include soils with andic soil properties (high amounts of poorly crystalline, amorphous minerals) and soils with high contents of gypsum (more than about 25 percent). For soils like these, for which the estimated field texture class and the laboratory measured particle-size distribution differ markedly, the field texture is referred to as *apparent* because it is not an estimate that correlates well with the results of a laboratory test. Apparent field texture is only a tactile evaluation and does not infer laboratory test results. The twelve texture classes (fig. 3-7) are sands, loamy sands, sandy loams, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. Subclasses of sand are coarse sand, sand, fine sand, and very fine sand. Subclasses of loamy sands and sandy loams that are based on sand size are named similarly.

Definitions of Soil Texture Classes and Subclasses

Sands.—Material has more than 85 percent sand, and the percentage of silt plus 1.5 times the percentage of clay is less than 15.

Coarse sand.—Material has a total of 25 percent or more very coarse and coarse sand and less than 50 percent any other single grade of sand.

Sand.—Material has a total of 25 percent or more very coarse, coarse, and medium sand, a total of less than 25 percent very coarse and coarse sand, and less than 50 percent fine sand and less than 50 percent very fine sand; OR material has 25 percent or more very coarse and coarse sand and 50 percent or more medium sand.

Fine sand.—Material has 50 percent or more fine sand, and fine sand exceeds very fine sand; OR material has a total of less than 25 percent very coarse, coarse, and medium sand and less than 50 percent very fine sand.

Very fine sand.—Material has 50 percent or more very fine sand.

Loamy sands.—Material has between 70 and 90 percent sand, the percentage of silt plus 1.5 times the percentage of clay is 15 or more, and the percentage of silt plus twice the percentage of clay is less than 30.

Loamy coarse sand.—Material has a total of 25 percent or more very coarse and coarse sand and less than 50 percent any other single grade of sand.

Loamy sand.—Material has a total of 25 percent or more very coarse, coarse, and medium sand, a total of less than 25 percent very coarse and coarse sand, and less than 50 percent fine sand and less than 50 percent very fine sand; OR material has a total of 25 percent or more very coarse and coarse sand and 50 percent or more medium sand.

Loamy fine sand.—Material has 50 percent or more fine sand or less than 50 percent very fine sand and a total of less than 25 percent very coarse, coarse, and medium sand.

Loamy very fine sand.—Material has 50 percent or more very fine sand.

Sandy loams.—Material has 7 to less than 20 percent clay and more than 52 percent sand, and the percentage of silt plus twice the percentage of clay is 30 or more; OR material has less than 7 percent clay and less than 50 percent silt, and the percentage of silt plus twice the percentage of clay is 30 or more.

Coarse sandy loam.—Material has a total of 25 percent or more very coarse and coarse sand and less than 50 percent any other single grade of sand; OR material has a total of 30 percent or more very coarse, coarse, and medium sand, and very fine sand is 30 to less than 50 percent.

Sandy loam.—Material has a total of 30 percent or more very coarse, coarse, and medium sand but a total of less than 25 percent very coarse and coarse sand, less than 30 percent fine sand, and less than 30 percent very fine sand; OR material has a total of 15 percent or less very coarse, coarse, and medium sand, less than 30 percent fine sand, and less than 30 percent very fine sand with a total of 40 percent or less fine and very fine sand; OR material has a total of 25 percent or more very coarse and coarse sand and 50 percent or more medium sand.

Fine sandy loam.—Material has 30 percent or more fine sand, less than 30 percent very fine sand, and a total of less than 25 percent very coarse and coarse sand; OR material has a total of 15 to less than 30 percent very coarse, coarse, and medium sand and a total of less than 25 percent very coarse and coarse sand; OR material has a total of 40 percent or more fine and very fine sand (and fine sand equals or exceeds very fine sand) and a total of 15 percent or less very coarse, coarse, and medium sand; OR material has a total of 25 percent or more very coarse and coarse sand and 50 percent or more fine sand.

Very fine sandy loam.—Material has 30 percent or more very fine sand and a total of less than 15 percent very coarse, coarse, and medium sand, and very fine sand exceeds fine sand; OR material has 40 percent or more fine and very fine sand (and very fine sand exceeds fine sand) and a total of less than 15 percent very coarse, coarse, and medium sand; OR material has 50 percent or more very fine sand and a total of 25 percent or more very coarse and coarse sand; OR material has a total of 30 percent or more very coarse, coarse, and medium sand and 50 percent or more very fine sand.

Loam.—Material has 7 to less than 27 percent clay, 28 to less than 50 percent silt, and 52 percent or less sand.

Silt loam.—Material has 50 percent or more silt and 12 to less than 27 percent clay; OR material has 50 to less than 80 percent silt and less than 12 percent clay.

Silt.—Material has 80 percent or more silt and less than 12 percent clay.

Sandy clay loam.—Material has 20 to less than 35 percent clay, less than 28 percent silt, and more than 45 percent sand.

Clay loam.—Material has 27 to less than 40 percent clay and more than 20 to 45 percent sand.

Silty clay loam.—Material has 27 to less than 40 percent clay and 20 percent or less sand.

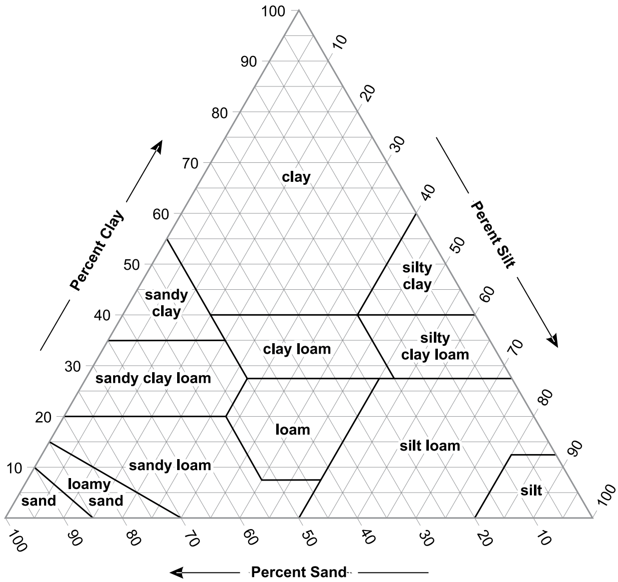
Sandy clay.—Material has 35 percent or more clay and more than 45 percent sand.

Silty clay.—Material has 40 percent or more clay and 40 percent or more silt.

Clay.—Material has 40 percent or more clay, 45 percent or less sand, and less than 40 percent silt.

The USDA textural triangle is shown in figure 3-7. A soil sample is assigned to one of the twelve soil texture classes according to the values for the proportions of sand, silt, and clay, which are located along each of the three axes. The eight subclasses in the sand and loamy sand groups provide refinement that in some cases may be greater than can be consistently determined by field techniques. Only those distinctions that are significant to use and management and that can be consistently made in the field should be applied when determinations of texture are based on field estimates alone.

Figure 3-7



USDA textural triangle showing the percentages of clay, silt, and sand in the 12 basic texture classes.

Groupings of Soil Texture Classes

The need for fine distinctions in the texture of the soil layers results in a large number of classes and subclasses of soil texture. It commonly is convenient to speak generally of broad groups or classes of texture. Table 3-1 provides an outline of three general soil texture groups and five subgroups. In some areas where soils have a high content of silt, a fourth general class, silty soil materials, may be used for silt and silt loam.

Terms Used *in Lieu* of Soil Texture

There are some horizons or layers for which soil texture class terms are not applicable. These include bedrock and other cemented horizons (such as petrocalcic horizons, duripans, etc.), those composed of organic soil materials, and those composed of water, either liquid or frozen, below a mineral or organic soil surface layer. Other exceptions include layers composed of more than 90 percent rock fragments or artifacts and horizons or layers composed of 40 percent or more gypsum in the fine-earth fraction (and that are not cemented). These exceptions are discussed below.

Table 3-1

General Soil Texture Groups

General texture groups and subgroups*	Texture classes
Sandy soil materials	
Coarse textured	Sands (coarse sand, sand, fine sand, very fine sand); loamy sands (loamy coarse sand, loamy sand, loamy fine sand, loamy very fine sand)
Loamy soil materials	
Moderately coarse textured	Coarse sandy loam, sandy loam, fine sandy loam
Medium textured	Very fine sandy loam, loam, silt loam, silt
Moderately fine textured	Clay loam, sandy clay loam, silty clay loam
Clayey soil materials	
Fine textured	Sandy clay, silty clay, clay

* Note: These are not the sandy, loamy, and clayey family particle-size classes defined in *Soil Taxonomy*.

Soil Materials with a High Content of Gypsum

For soil materials with 40 percent or more, by weight, gypsum in the fine-earth fraction, gypsum dominates the physical and chemical properties of the soil to the extent that particle-size classes are not meaningful. Two terms *in lieu* of texture are used:

Coarse gypsum material.—50 percent or more of the fine-earth fraction is comprised of particles ranging from 0.1 to 2.0 mm in diameter.

Fine gypsum material.—Less than 50 percent of the fine-earth fraction is comprised of particles ranging from 0.1 to 2.0 mm in diameter.

Bedrock and Cemented Horizons

These horizons or layers are described as *bedrock* or *cemented material*. Additional information about the kind of rock, degree of cementation, and kind of cementing agent can also be provided.

Water Layers

These layers are described as *water* or *ice*. They only refer to subsurface layers, such as in a floating bog. Figure 3-3 shows a subsoil layer of ice.

Soil Materials with a High Content of Rock or Pararock Fragments

For soil materials with more than 90 percent rock or pararock fragments, there is not enough fine earth to determine the texture class. In these cases, the terms *gravel*, *cobbles*, *stones*, *boulders*, *channers*, and *flagstones* or their pararock fragment equivalents are used. Size range and shape for these terms are described under "Rock Fragments and Pararock Fragments" and are summarized in table 3-2.

Soil Materials with a High Content of Artifacts

For soil materials with more than 90 percent artifacts, the term *artifacts* is used.

Organic Soils

Layers that are not saturated with water for more than a few days at a time are organic if they have 20 percent or more organic carbon. Layers that are saturated for longer periods, or were saturated before being drained, are organic if they have 12 percent or more organic carbon and no clay, 18 percent or more organic carbon, and 60 percent or more clay or have a proportional amount of organic carbon, between 12 and 18 percent, if the clay content is between 0 and 60 percent. The required organic carbon content for saturated soils having between 0 and 60 percent clay can be calculated as: $OC_{required} = 12 + (0.1 * \text{percent clay})$. Soils with more than 60 percent clay need an organic carbon content of at least 18 percent.

The kind and amount of the mineral fraction, the kind of organisms from which the organic material was derived, and the state of decomposition affect the properties of the soil material. Descriptions include the percentage of undecomposed fibers and the solubility in sodium pyrophosphate of the humified material. Attention should be given to identifying and estimating the volume occupied by *sphagnum* fibers, which have extraordinary high water retention. When squeezed firmly in the hand to remove as much water as possible, *sphagnum* fibers are lighter in color than fibers of *hypnum* and most other mosses.

Fragments of wood more than 20 mm across and so undecomposed that they cannot be crushed by the fingers when moist or wet are called *wood fragments*. They are comparable to rock fragments in mineral soils and are described in a comparable manner.

Saturated organic soil materials.—The types of organic soil materials that are described in saturated organic soil materials are:

Muck.—Well decomposed organic soil material with a low content of fibers (plant tissue excluding live roots).
Peat.—Slightly decomposed organic soil material with a high content of original fibers.
Mucky peat.—Organic soil material that is intermediate in degree of decomposition, fiber content, bulk density, and water content between muck and peat.

Muck, peat, and mucky peat may be described in both organic and mineral soils provided the soils are saturated with water for 30 or more cumulative days in normal years or are artificially drained. These materials only qualify for the diagnostic sapric, fibric, and hemic soil material of Soil Taxonomy when they occur in organic soils (i.e., the soil of the order Histosols and the suborder Histels).

Non-saturated organic soil materials.—The types of organic soil materials that are described in layers not saturated for 30 or more cumulative days are:

Highly decomposed plant material.—Well decomposed, organic soil material with a low content of fibers (plant tissue excluding live roots).
Moderately decomposed plant material.—Material intermediate in degree of decomposition, fiber content, bulk density, and water content between highly decomposed and slightly decomposed plant material.
Slightly decomposed plant material.—Slightly decomposed organic soil material with a high content of original fibers.

Modifiers for Terms Used *in Lieu* of Texture

Modifiers may be needed to better describe the soil material making up the horizon or layer. These include terms for significant amounts of particles 2.0 mm or larger (rock fragments, pararock fragments, or artifacts) and terms that indicate the composition of the soil material.

Soil Materials with Rock Fragments, Pararock Fragments, or Artifacts

To describe soils with 15 percent or more, by volume, rock fragments, pararock fragments, or artifacts, the texture terms are modified with terms indicating the amount and kind of fragments. Examples include very gravelly loam, extremely paracobbly sand, and very artifactual sand. The conventions for use of these terms and the definitions of class terms are discussed in the following sections on rock fragments, pararock fragments, and artifacts.

Class Modifiers Indicating Soil Material Composition

Soil composition modifiers are used for some soils that have andic properties or formed in volcanic materials, soils that have a high content of gypsum, some organic soil materials, and mineral soil materials with a high content of organic matter. Terms are also provided for limnic soil materials and permanently frozen layers (permafrost).

Soil Materials with Andic Properties or Volcanic Origin

Hydrous.—Material that has andic soil properties and an undried 15 bar (1500 kPa) water content of 100 percent or more of the dry weight (e.g., hydrous clay).

Medial.—Material that has andic soil properties and has a 15 bar (1500 kPa) water content of less than 100 percent on undried samples and of 12 percent or more on air-dried samples (e.g., medial silt loam).

Ashy.—Material that has andic soil properties and is neither hydrous nor medial, or material that does not have andic soil properties and the chemistry and physical makeup of its fine-earth fraction reflects the weathering processes of volcanic materials (e.g., ashy loam). The weathering processes of volcanic materials are evidenced by 30 percent or more particles 0.02 to 2.0 mm in diameter, of which 5 percent or more is composed of volcanic glass and the [(aluminum plus ½ iron percent by ammonium oxalate) times 60] plus the volcanic glass percent is equal to or more than 30.

Soil Materials with Gypsum

Gypsiferous.—Material that contains 15 to less than 40 percent, by weight, gypsum (e.g., gypsiferous fine sandy loam).

For material that has 40 percent or more gypsum, a term *in lieu* of texture is used (e.g., *fine gypsum material* or *coarse gypsum material,* defined above).

Organic Soil Materials

Modifiers are only used with the "*in lieu* of texture" terms *muck*, *peat*, or *mucky peat*. The following modifiers are used only for organic soil materials that are saturated with water for 30 or more cumulative days in normal years or are artificially drained.

Woody.—Material contains 15 percent or more wood fragments larger than 20 mm in size or contains 15 percent or more fibers that can be identified as wood origin and has more wood fibers than any other kind of fiber (e.g., woody muck).

Grassy.—Material contains more than 15 percent fibers that can be identified as grass, sedges, cattails, and other grasslike plants and contains more grassy fibers than any other kind of fiber (e.g., grassy mucky peat).

Mossy.—Material contains more than 15 percent fibers that can be identified as moss and contains more moss fibers than any other kind of fiber (e.g., mossy peat).

Herbaceous.—Material contains more than 15 percent fibers that can be identified as herbaceous plants other than moss and grass or grasslike plants and has more of these fibers than any other kind of fiber (e.g., herbaceous muck).

Mineral Soil Materials with a High Content of Organic Matter

Highly organic.—Term indicates near surface horizons of mineral soils that are saturated with water for less than 30 cumulative days in normal years and are not artificially drained (e.g., highly organic loam). Excluding live roots, the horizon has organic carbon content (by weight) of one of the following:

- 5 to < 20 percent if the mineral fraction contains no clay,
- 12 to < 20 percent if the mineral fraction contains 60 percent or more clay, or
- [5 + (clay percentage multiplied by 0.12)] to < 20 percent if the mineral fraction contains less than 60 percent clay.

Mucky.—Term indicates near surface horizons of mineral soils that are saturated with water for 30 or more cumulative days in normal years or are artificially drained (e.g., mucky silt loam). Excluding live roots, the horizon has more than 10 percent organic matter and less than 17 percent fibers.

Peaty.—Term indicates near surface horizons of mineral soils that are saturated with water for 30 or more cumulative days in normal years or are artificially drained (e.g., peaty clay loam). Excluding live roots, the horizon has more than 10 percent organic matter and 17 percent or more fibers.

Limnic Soil Materials

Limnic soil materials occur in layers underlying some soils of the soil order Histosols. By definition (see *Soil Taxonomy*) they are not recognized in mineral soils. They are mineral or organic soil materials originating from aquatic organisms or from aquatic plants that were later altered by aquatic organisms. The following terms are used to describe the origin of the limnic materials:

Coprogenous.—Material contains many very small (0.1 to 0.001 mm) fecal pellets (e.g., coprogenous sandy loam).

Diatomaceous.—Material is composed dominantly of diatoms (e.g., diatomaceous silt loam).

Marly.—Material is composed dominantly of calcium carbonate "mud" (e.g., marly silty clay).

Layers for which these terms are used may or may not also meet the definition for coprogenous earth, diatomaceous earth, or marl as defined in *Soil Taxonomy*.

Permafrost

Layers of permafrost are described as *permanently frozen* (e.g., permanently frozen loamy sand).

Rock Fragments and Pararock Fragments

Rock fragments are unattached pieces of geologic or pedogenic material 2 mm in diameter or larger that have a *strongly cemented* or more cemented rupture-resistance class. Pararock fragments are unattached pieces of geologic or pedogenic material 2 mm in diameter or larger that are *extremely weakly cemented* through *moderately cemented*. Pararock fragments are not retained on sieves because they are crushed by grinding during the preparation of samples for particle-size analysis in the laboratory. Rock fragments and pararock fragments include all sizes between 2.0 mm and horizontal dimensions smaller than the size of a pedon. The words "rock" and "pararock" are used here in the broad sense and connote more than just natural fragments of geologic material. Thus, rock and pararock fragments may be discrete, cemented pieces of bedrock, bedrock-like material, durinodes, concretions, nodules, or pedogenic horizons (e.g., petrocalcic fragments). Artifacts, however, are not included as rock or pararock fragments. They are described separately.

Rock fragments and pararock fragments are described by size, shape, hardness, roundness, and kind of fragment. The classes are *gravel,* *cobbles, channers, flagstones, stones,* and *boulders* and their pararock counterparts (i.e., *paragravel, paracobbles*, etc.) (table 3-2). If a size or range of sizes predominates, the class is modified (e.g., "fine gravel," "cobbles 100 to 150 mm in diameter," "channers 25 to 50 mm in length").

Gravel and *paragravel* are a collection of fragments that have diameters ranging from 2 to 76 mm. Individual fragments in this size range are properly referred to as "pebbles," not "gravels." The term gravel as used here indicates the collection of pebbles in a soil horizon and does not imply a geological formation. The terms "pebble" and "cobble" are typically restricted to rounded or subrounded fragments; however, they can be used to describe angular fragments that are not flat. Words such as "chert," "limestone," and "shale" refer to a kind or lithology of rock, not a piece of rock. The composition of the fragments can be given, for example: "chert gravel," "limestone channers," "siltstone parachanners."

The upper size limit of gravel and paragravel is 76 mm (3 inches). This coincides with the upper limit used by many engineers for grain-size distribution computations. The 5-mm and 20-mm divisions for the separation of fine, medium, and coarse gravel coincide with the sizes of openings in the number 4 screen (4.76-mm) and the ¾-inch (19.05-mm) screen used in engineering.

The 76-mm (3-inch) limit separates gravel from cobbles, the 250-mm (10-inch) limit separates cobbles from stones, and the 600-mm (24-inch) limit separates stones from boulders. The 150-mm (6-inch) and 380-mm (15-inch) limits for thin, flat channers and flagstones, respectively, follow conventions used for many years to provide class limits for plate-shaped and crudely spherical rock fragments that have about the same soil use implications as the 250-mm limit for spherical shapes.

Estimating Rock Fragments in the Soil

Rock fragments in the soil can greatly influence use and management. It is important to not only consider the total amount of rock fragments, but also the proportions of the various size classes (gravel, cobbles, stones, etc.). A soil with 10 percent stones is quite different from one with 10 percent gravel. When developing interpretive criteria, a distinction must be made between volume and weight percent of rock fragments. Field descriptions generally record estimates of volume, while laboratory measurements of rock fragments are given as weight for the various size classes.

The National Cooperative Soil Survey in the United States uses interpretive algorithms based on weight percent of the > 250, > 76-250, > 5-76, and 2-5 mm fractions when rating soils for various potential uses.

The first two size ranges are on a whole soil basis, and the latter two are on a < 76 mm basis. For the > 250 and > 76-250 mm fractions, weighing is generally impracticable and volume percentage estimates are made from areal percentage measurements by point-count or line-intersect methods. Length of the transect or area of the exposure should be at least 50 times, and preferably 100 times, the area or dimensions of the rock fragment size that encompasses about 90 percent of the rock fragment volume. For the < 76 mm weight, measurements are feasible but may require 50 to 60 kg of sample if appreciable rock fragments near 76 mm are present. An alternative is to obtain volume estimates for the 20-76 mm fraction and weight estimates for the < 20 mm fraction. This method is preferred because of the difficulty in visual evaluation of the 2 to 5 mm size separations. The weight percentages of > 5-20 mm and 2-5 mm fractions may be converted to volume estimates and placed on a < 76 mm base by computation.

Terms for Rock Fragments and Their Use in Modifying Texture Classes

The adjectival form of a class name of rock fragments or pararock fragments (table 3-2) is used as a modifier of the texture class name, e.g., paragravelly loam, very cobbly sandy loam. Table 3-3 provides rules for determining the proper texture modifier term for material with a mixture of rock fragment sizes. This section also provides rules for assigning terms for soils with a mixture of rock and pararock fragments.

The following classes, based on volume percentages, are used:

Less than 15 percent.—No texture modifier terms are used with soils having less than 15 percent gravel, paragravel, cobbles, paracobbles, channers, parachanners, flagstones, or paraflagstones.

15 to less than 35 percent.—The adjectival term of the dominant kind of fragment is used as a modifier of the texture class, e.g., gravelly loam, parachannery silt loam, cobbly sandy loam.

35 to less than 60 percent.—The adjectival term of the dominant kind of rock fragment is used with the word "very" as a modifier of the texture class, e.g., very gravelly loam, very parachannery silt loam, very cobbly loamy sand (fig. 3-8).

60 to less than 90 percent.—The adjectival term of the dominant kind of rock fragment is used with the word "extremely" as a modifier of the texture class, e.g., extremely gravelly loam, extremely parachannery silt loam, extremely cobbly sandy loam.

Table 3-2

Terms for Rock Fragments and Pararock Fragments

Shape and size	Noun*	Adjective*
Nonflat fragments (spherical or cubelike):		
2–76 mm diameter	Gravel	Gravelly
2–5 mm diameter	Fine gravel	Fine gravelly
> 5–20 mm diameter	Medium gravel	Medium gravelly
> 20–76 mm diameter	Coarse gravel	Coarse gravelly
> 76–250 mm diameter	Cobbles	Cobbly
> 250–600 mm diameter	Stones	Stony
> 600 mm diameter	Boulders	Bouldery
Flat fragments:		
2–150 mm long	Channers	Channery
> 150–380 mm long	Flagstones	Flaggy
> 380–600 mm long	Stones	Stony
> 600 mm long	Boulders	Bouldery

* For fragments that are less than strongly cemented, the prefix "para" is added to the terms in this table to form either a descriptive noun or the adjective for the texture modifier (e.g., paracobbles, paragravelly).

90 percent or more.—No texture modifier terms are used. If there is too little fine earth to determine the texture class (less than about 10 percent, by volume) a term *in lieu* of texture (i.e., gravel, cobbles, stones, boulders, channers, flagstones, or their pararock fragment equivalents) is used as appropriate.

The class limits apply to the volume of the layer occupied by all rock fragments 2 mm in diameter or larger. The soil generally contains fragments smaller or larger than those identified by the term. For example, very cobbly sandy loam typically contains gravel but "gravelly" is not in the name. The use of a term for larger pieces of rock, such as boulders, does not imply that the pieces are entirely within a given soil layer. A single boulder may extend through several layers.

Table 3-3 can be used to determine the proper modifier if there is a mixture of rock fragment sizes. To use the table, first choose the row with the appropriate total rock fragments. Then read the criteria in the columns under "Gravel, cobbles, stones, and boulders," starting from the

Figure 3-8

A soil in which the layers below a depth of about 20 cm are very cobbly loamy sand. Left side of scale is in 20-cm increments.

Table 3-3

Guide for Determining Rock Fragment Modifier of Texture for Soils with a Mixture of Rock Fragment Sizes

Total rock fragments *(Vol. %)*	Gravel (GR), cobbles (CB), stones (ST), and boulders (BY) (Substitute channers for gravel and flagstones for cobbles, where applicable)			
	If GR ≥ 1.5 CB + 2 ST + 2.5 BY	If CB ≥ 1.5 ST + 2 BY	If ST ≥ 1.5 BY	If ST < 1.5 BY
≥ 15 < 35	Gravelly	Cobbly	Stony	Bouldery
≥ 35 < 60	Very gravelly	Very cobbly	Very stony	Very bouldery
≥ 60 < 90	Extremely gravelly	Extremely cobbly	Extremely stony	Extremely bouldery
≥ 90	Gravel	Cobbles	Stones	Boulders

left-most column and proceeding to the right. Stop in the first column in which a criterion is met.

More precise estimates of the amounts of rock fragments than are provided by the defined classes are needed for some purposes. For more precise information, estimates of percentages of each size class or a combination of size classes are included in the description, e.g., "very cobbly sandy loam," "30 percent cobbles and 15 percent gravel or silt loam," "about 10 percent gravel." If loose pieces of rock are significant to the use and management of a soil, they are the basis of phase distinctions among map units. Exposed bedrock is not soil and is identified separately in mapping as a kind of miscellaneous area (i.e., Rock outcrop).

The volume occupied by individual pieces of rock can be seen, and their aggregate volume percentage can be calculated. For some purposes, volume percentage must be converted to weight percentage.

The following rules are used to select texture modifiers if a horizon includes both rock and pararock fragments:

1. Describe the individual kinds and amounts of rock and pararock fragments.
2. Do not use a fragment texture modifier if the combined volume of rock and pararock fragments is less than 15 percent.
3. If the combined volume of rock and pararock fragments is more than 15 percent and the volume of rock fragments is less than 15 percent, assign pararock fragment modifiers based on the combined volume of fragments. For example, use "paragravelly" as a texture modifier for soils with 10 percent rock and 10 percent pararock gravel-sized fragments.
4. If the volume of rock fragments is 15 percent or more, use the appropriate texture modifier for rock fragments regardless of the volume of pararock fragments.

Rock Fragment Hardness, Roundness, and Kind

Fragment hardness is equivalent to the rupture resistance class for a cemented fragment of specified size that has been air dried and then submerged in water. The hardness of a fragment is significant where the rupture resistance class is strongly cemented or greater. See the section on rupture resistance later in this chapter for details describing the fragment hardness classes and their test descriptions.

Fragment roundness is an expression of the sharpness of the edges and corners of rock fragments and pararock fragments. The roundness of fragments impacts water infiltration, root penetration, and macropore space. The following roundness classes are used:

Very angular	Strongly developed faces and very sharp, broken edges
Angular..................	Strongly developed faces and sharp edges
Subangular.............	Detectable flat faces and slightly rounded corners
Subrounded............	Detectable flat faces and well rounded corners
Rounded.................	Flat faces absent or nearly absent and all corners rounded
Well rounded	Flat faces absent and all corners rounded

Fragment kind is the lithology or composition of the 2 mm or larger fraction of the soil. Kinds of fragments are varied based on whether their origin is from a geologic source or a pedogenic source. Examples of kinds of fragments are basalt fragments, durinodes, iron-manganese concretions, limestone fragments, petrocalcic fragments, tuff fragments, and wood fragments.

Artifacts

Artifacts are discrete water-stable objects or materials created, modified, or transported from their source by humans, usually for a practical purpose in habitation, manufacturing, excavation, agriculture, or construction activities. Examples are processed wood products, coal combustion by-products, bitumen (asphalt), fibers and fabrics, bricks, cinder blocks, concrete, plastic, glass, rubber, paper, cardboard, iron and steel, altered metals and minerals, sanitary and medical waste, garbage, and landfill waste. Artifacts also include natural materials which were mechanically abraded by human activities (as evidenced by scrapes, gouges, tool marks, etc.), such as shaped or carved stone work, grindstones, and shaped stones and debitage (e.g., stone tool flakes).

Artifacts are generally categorized as either *particulate* or *discrete*. The distinction is based on size: particulate artifacts have a diameter of less than 2 mm and discrete artifacts have a diameter of 2 mm or more. Discrete artifacts are easier to identify and are essentially fragments of human origin. Particulate artifacts are sometimes difficult to discern from naturally occurring fine-earth soil material.

Describing Artifacts in Soil

Artifacts are described if they are judged to be durable enough to persist in the soil (resist weathering and leaching) for a few decades or more. Descriptions of artifacts generally include quantity, cohesion, persistence, size, and safety classes. They may also include shape, kind, penetrability by roots, and roundness. Additional attributes (such as those discussed below under the heading "Consistence") may be described to help understand and interpret the soil. The conventions for describing artifacts are explained in the following paragraphs.

Quantity refers to the estimated volume percent of a horizon or other specified unit occupied by discrete artifacts. If classes (rather than quantitative estimates) are given, they are the same as those described in this chapter for mottles.

Cohesion refers to the relative ability of the artifact to remain intact after significant disturbance. The cohesion classes are:

Cohesive.—Artifacts adhere together sufficiently so that they cannot be easily broken into pieces < 2 mm either by hand or with a simple crushing device, such as a mortar and pestle.

Noncohesive.—Artifacts are easily broken into pieces < 2 mm either by hand or with a simple crushing device, such as a mortar and pestle. Noncohesive artifacts are similar to pararock fragments and will be incorporated into the fine-earth fraction of the soil during routine laboratory sample preparation.

Penetrability describes the relative ease with which roots can penetrate the artifact and potentially extract any stored moisture, nutrients, or toxic elements. The penetrability classes are:

Nonpenetrable.—Roots cannot penetrate through the solid parts of the artifact or between the component parts of the artifact.

Penetrable.—Roots can penetrate through the solid parts of the artifact or between the component parts of the artifact.

Persistence describes the relative ability of solid artifacts to withstand weathering and decay over time. Local conditions, such as temperature and moisture, significantly impact the persistence of artifacts in the soil. The persistence classes are:

Nonpersistent.—The artifact is susceptible to relatively rapid weathering or decay and is expected to be lost from the soil in less than a decade. Loss of soil mass and eventually subsidence result.

Persistent.—The artifact is expected to remain intact in the soil for a decade or more.

Roundness indicates the sharpness of edges and corners of natural objects, such as rock fragments, and human-manufactured objects, such as artifacts. The artifact roundness classes are the same as those used for fragment roundness (above).

Safety describes the degree of risk to humans from contact with soils that contain artifacts. Physical contact with soils containing dangerous or harmful artifacts should be avoided unless proper training is provided and protective clothing is available. The safety classes are:

Innocuous.—The artifacts are considered to be harmless to living beings. Examples include untreated wood products, iron, bricks, cinder blocks, concrete, plastic, glass, rubber, organic fibers, inorganic fibers, unprinted paper and cardboard, and some mineral and metal products. Sharp innocuous artifacts can cause injury, but the materials themselves are still considered innocuous.

Noxious.—The artifacts are potentially harmful or destructive to living beings unless dealt with carefully. The harm may be immediate or long-term and through direct or indirect contact. Examples include arsenic-treated wood products, batteries, waste and garbage, radioactive fallout, liquid petroleum products, asphalt, coal ash, paper printed with metallic ink, and some mineral and metal products.

Shape is variable among kinds of artifacts. The shape classes are:

Elongated.—One dimension is at least three times longer than both of the others.

Equidimensional.—Dimensions in length, width, and height are approximately similar.

Flat.—One dimension is less than one third that of both of the others, and one dimension is less than three times that of the intermediate dimension.

Irregular.—The form is branching and convoluted.

Size may be measured and reported directly or given as a class. The dimension to which size-class limits apply depends on the shape of the artifact described. If the shape is nearly uniform, size is measured in the shortest dimension, such as the effective diameter of a cylinder or the thickness of a plate. For elongated or irregular bodies, size generally refers to the longest dimension but direct measurements for 2 or 3 dimensions can be given for clarification. The size classes for discrete artifacts are:

Fine........................ 2 to < 20 mm
Medium .... 20 to < 75 mm
Coarse.................... 75 to < 250 mm
Very coarse .... ≥ 250 mm

Kinds of Artifacts

There are too many varieties of artifacts to provide a comprehensive list. The most common types include:

- Noxious and innocuous artifacts
- Treated and untreated wood products
- Liquid petroleum products
- Coal combustion by-products
- Paper (printed and unprinted) and cardboard
- Sanitary and medical waste
- Garbage and landfill waste
- Asphalt
- Organic and inorganic fibers
- Bricks
- Cinder blocks
- Concrete
- Plastic
- Glass
- Rubber products
- Iron and steel

Texture Modifier Terms for Soils with Artifacts

The texture of soils with artifacts is described according to the content of artifacts:

Less than 15 percent.—No texture modifier terms are used.

15 to less than 35 percent.—The term "artifactual" is used, e.g., artifactual loam.

35 to less than 60 percent.—The term "very artifactual" is used, e.g., very artifactual loam.

60 to less than 90 percent.—The term "extremely artifactual" is used, e.g., extremely artifactual loam.

90 percent or more.—No texture modifier terms are used. If there is not enough fine earth to determine the texture class (less than about 10 percent, by volume) the term "artifacts" is used.

Compound Texture Modifiers

In some cases, the mineral soil may contain a combination of fragment or composition types for which the use of compound texture modifiers is useful. For example, a soil horizon may contain both artifacts and other fragments, such as rock fragments and pararock fragments. In these cases, the rock fragments, pararock fragments, and artifacts are each described separately. Modifiers for both artifacts and rock or pararock fragments can be combined. The modifier for artifacts comes before the modifier for rock or pararock fragments, e.g., artifactual very gravelly sandy loam. Modifiers for composition and rock fragments can also be combined. For example, a horizon of channery mucky clay or one of gravelly gypsiferous sandy loam contains rock fragments and also a content of high organic matter or gypsum. There are many possible combinations.

Fragments on the Surface

This section discusses the description of rock fragments (especially stones and boulders) that are *on the soil* as opposed to *in the soil*. The description of gravel, cobbles, and channers (≥ 2 but < 250 mm in diameter) differs from that for stones and boulders (≥ 250 mm in diameter) because an important aspect of gravel, cobbles, and channers is their areal percent cover on the ground surface. This cover provides some protection from wind and water erosion. It may also interfere with seed placement and emergence after germination. For stones and boulders, the percent of cover is not of itself as important as the interference with mechanical manipulation of the soil. For example, a very small areal percentage of large fragments, insignificant for erosion protection, may interfere with tillage, tree harvesting, and other operations involving machinery.

The areal percentage of the ground surface is determined using point-count and/or line-intersect procedures. If the areal percentage equals or exceeds 80 percent, the top of the soil is considered to be the mean height of the top of the rock or pararock fragments. The volume proportions of the 2 to 5 mm, 5 to 75 mm, and 75 to 250 mm fragments should be recorded. This can be done from areal measurements in representative areas.

The number, size, and spacing of stones and boulders (≥ 250 mm in diameter) on the surface of a soil, including both those that lie on the surface and those that are partly within the soil, have important effects on soil use and management. The classes are given in terms of the approximate amount of rock fragments of stone and boulder size at the surface:

Class 1.—Stones or boulders cover 0.01 to less than 0.1 percent of the surface. The smallest stones are at least 8 meters apart; the smallest boulders are at least 20 meters apart (fig. 3-9).

Class 2.—Stones or boulders cover 0.1 to less than 3 percent of the surface. The smallest stones are not less than 1 meter apart; the smallest boulders are not less than 3 meters apart (fig. 3-10).

Class 3.—Stones or boulders cover 3 to less than 15 percent of the surface. The smallest stones are as little as 0.5 meter apart; the smallest boulders are as little as 1 meter apart (fig. 3-11).

Class 4.—Stones or boulders cover 15 to less than 50 percent of the surface. The smallest stones are as little as 0.3 meter apart; the smallest boulders are as little as 0.5 meter apart. In most places it is possible to step from stone to stone or jump from boulder to boulder without touching the soil (fig. 3-12).

Class 5.—Stones or boulders appear to be nearly continuous and cover 50 percent or more of the surface. The smallest stones are less than 0.03 meter apart; the smallest boulders are less than 0.05 meter apart. Classifiable soil is among the rock fragments, and plant growth is possible (fig. 3-13).

These limits are intended only as guides to amounts that may mark critical limitations for major kinds of land use. Table 3-4 is a summary of the classes.

Table 3-4

Classes of Surface Stones and Boulders in Terms of Cover and Spacing

Class	Percentage of surface covered	Distance in meters between stones or boulders if the diameter is:			Descriptive term
		0.25 m*	0.6 m	1.2 m	
1	0.01 to < 0.1	≥ 8	≥ 20	≥ 37	Stony or bouldery
2	0.1 to < 3.0	1–8	3–20	6–37	Very stony or very bouldery
3	3.0 to < 15	0.5–1	1–3	2–6	Extremely stony or extremely bouldery
4	15 to < 50	0.3–0.5	0.5–1	1–2	Rubbly
5	≥ 50	< 0.3	< 0.5	< 1	Very rubbly

* 0.38 m if the fragment is flat.

Figure 3-9

An area of bouldery soil (class 1).

Figure 3-10

An area of very bouldery soil (class 2).

Figure 3-11

An area of extremely bouldery soil (class 3).

Figure 3-12

An area of rubbly soil (class 4).

Figure 3-13

An area of very rubbly soil (class 5).

Soil Color

Most soil survey organizations, including the National Cooperative Soil Survey in the United States, have adopted the Munsell soil color system for describing soil color (using the elements of hue, value, and chroma). The names associated with each standard color chip (yellowish brown, light gray, etc.) are not strictly part of the Munsell color system. They were selected by the Soil Survey Staff to be used in conjunction with the Munsell color chips. The color chips included in the standard soil-color charts (a subset of all colors in the system) were selected so that soil scientists can describe the normal range of colors found in soils. These chips have enough contrast between them for different individuals to match a soil sample to the same color chip consistently. Interpolating between chips is not recommended in standard soil survey operations because such visual determinations cannot be repeated with a high level of precision. Although digital soil color meters that can provide precise color readings consistently are available, they are not widely used in field operations. Therefore, the standard procedure adopted for soil survey work is visual comparison to the standard soil-color charts.

Elements of Soil Color Descriptions

Elements of soil color descriptions are the color name, the Munsell notation, the water state (moist or dry), and the physical state. An example is "brown (10YR 5/3), dry, crushed and smoothed." Physical state is recorded as broken, rubbed, crushed, or crushed and smoothed. The term "crushed" typically applies to dry samples and "rubbed" to moist samples. If physical state is unspecified, a broken surface is implied. The color of the soil is normally recorded for a surface broken through a ped, if a ped can be broken as a unit. If ped surfaces are noticeably different in color from the ped interior, this should also be described.

The color value of most soil material is lower after moistening. Consequently, the water state of a sample is always given. The water state is either "moist" or "dry." The dry state for color determinations is air dry and should be made at the point where the color does not change with additional drying. Color in the moist state is determined on moderately moist or very moist soil material and should be made at the point where the color does not change with additional moistening. The soil should not be moistened to the extent that glistening takes place because the light reflection of water films may cause incorrect color determinations. In a humid region, the moist state generally is standard; in an arid region, the dry state is standard. In detailed descriptions, colors of both dry and moist soil are recorded if feasible. The color for the regionally standard moisture state is typically described first. Both moist and dry colors are valuable, particularly for the immediate surface and tilled horizons, in assessing reflectance.

A *Munsell notation* is obtained by comparison with a Munsell soil-color chart. The most commonly used charts include only about one fifth of the entire range of hues.[1] They consist of about 250 different colored papers, or chips, systematically arranged on hue cards according to their Munsell notations. Figure 3-14 illustrates the arrangements of color chips on a Munsell color card.

The Munsell color system uses three elements of color—*hue, value,* and *chroma*. The color notation is recorded as: hue, value/chroma (e.g., 5Y 6/3).

Hue is a measure of the chromatic composition of light that reaches the eye. The Munsell system is based on five principal hues: red (R), yellow (Y), green (G), blue (B), and purple (P). Five intermediate hues representing midpoints between each pair of principal hues complete the

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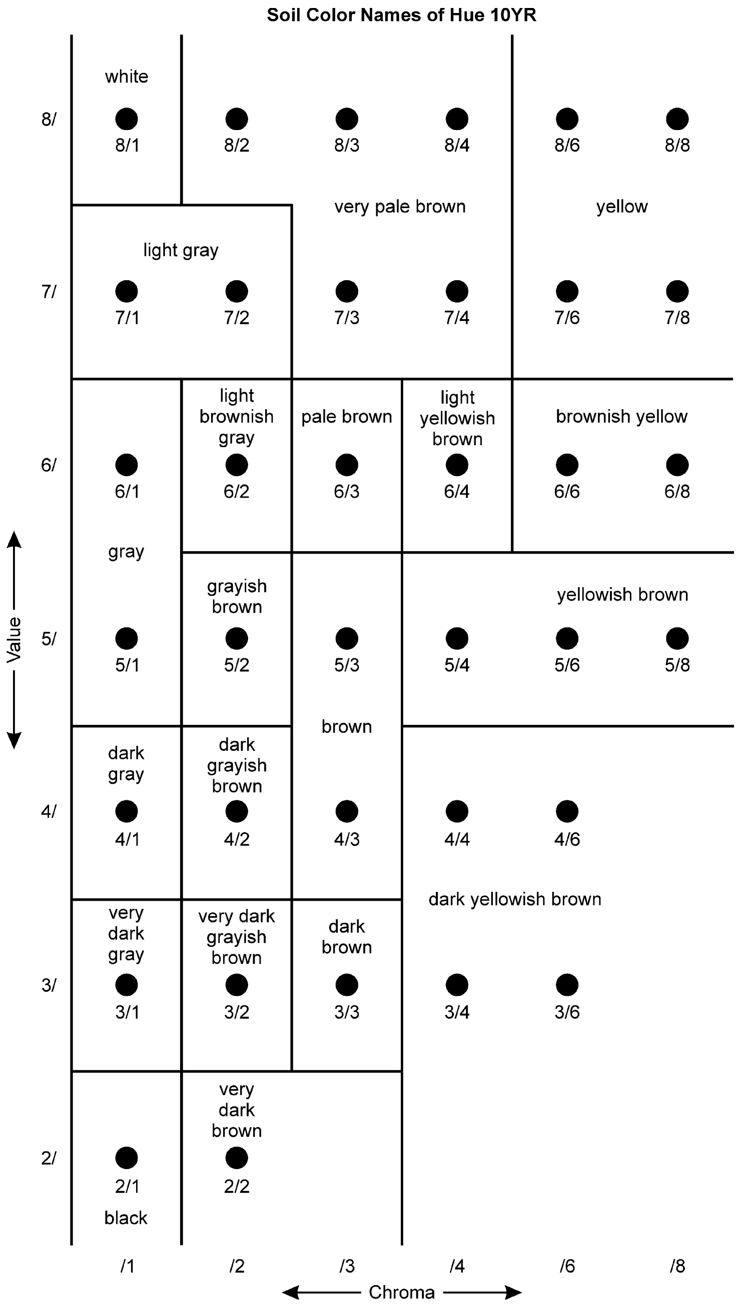
[1] The appropriate color chips, separate or mounted by hue on special cards for a loose-leaf notebook, are available through several suppliers of scientific equipment.

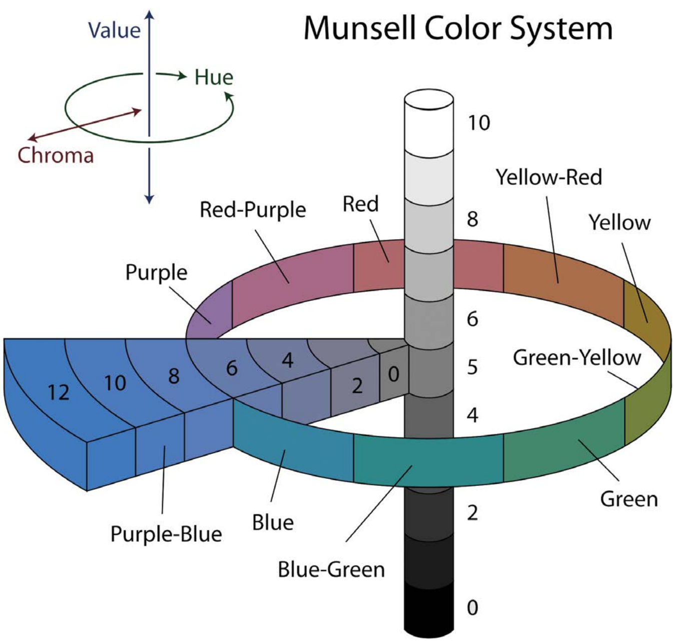
Figure 3-14



The arrangement of color chips according to value and chroma on the Munsell soil-color card of hue 10YR.

10 major hue names used to describe the notation. The intermediate hues are yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB), and red-purple (RP). The relationships among the 10 hues are shown in figure 3-15. Each of the 10 major hues is divided into 4 segments of equal visual steps, which are designated by numerical values applied as prefixes to the symbol for the hue name.[2] For example, 10R marks a limit of red hue. Four equally spaced steps of the adjacent yellow-red (YR) hue are identified as 2.5YR, 5YR, 7.5YR, and 10YR, respectively. The standard chart for soil has separate hue cards, from 10R through 5Y. In addition, special charts for gley colors and for very light colors are available.

Figure 3-15



A schematic diagram showing relationships among hue, value, and chroma in the Munsell color system (Rus, 2007).

Value indicates the degree of lightness or darkness of a color in relation to a neutral gray scale. On a neutral gray (achromatic) scale, value extends from pure black (0) to pure white (10). The value notation

[2] The notation for hue, value, and chroma is a decimal number that can be refined to any degree. In practice, however, only the divisions on the color charts are used.

is a measure of the amount of light that reaches the eye under standard lighting conditions. Gray is perceived as about halfway between black and white and has a value notation of 5. The actual amount of light that reaches the eye is related logarithmically to color value. Lighter colors are indicated by numbers between 5 and 10; darker colors are indicated by numbers from 5 to 0. These values may be designated for either achromatic (i.e., having no hue and chroma of 0) or chromatic (i.e., having all three components—hue, value, and chroma) conditions. Thus, a card of the color chart for soil has a series of chips arranged vertically to show equal steps from the lightest to the darkest shades of that hue. Figure 3-14 shows this arrangement vertically on the card for the hue of 10YR. Note that the highest value shown on the standard color cards is 8. Color chips with value of 9 are included on special color cards for very light colors.

Chroma is the relative purity or strength of the spectral color. It indicates the degree of saturation of neutral gray by the spectral color. The scales of chroma for soils extend from 0 (for neutral colors) to 8 (for colors with the strongest expression). The color chips are arranged horizontally by increasing chroma from left to right on the soil-color chart (see fig. 3-14).

On the soil-color chart for a specific hue (e.g., 10YR), the darkest shades of that hue are at the bottom of the card and the lightest shades are at the top. The weakest expression of chroma (the grayest color) is at the left, and the strongest expression of chroma is at the right.

At the extreme left of some cards are symbols such as N 6/. These colors have zero chroma and are totally achromatic (neutral). They have no hue and no chroma but range in value from black (N 2.5/) to white (N 8/). An example of a notation for a neutral (achromatic) color is N 5/ (gray). The color 10YR 5/1 is also called gray because the hue is hardly perceptible at such low chroma.

Conditions for Measuring Color

The quality and intensity of the light source affect the amount and quality of the light reflected. The moisture content of the sample and the roughness of its surface affect the light reflected. The visual impression of color from the standard color chips is accurate only under standard conditions of light intensity and quality. Color determination may be inaccurate early in the morning or late in the evening. When the sun is low in the sky or the atmosphere is smoky, the light reaching the sample and the light reflected are redder. Even though the same kind of light reaches the color standard and the sample, the reading of sample color at these times is commonly one or more intervals of hue redder than at midday. Colors also appear different in the subdued light of a cloudy day than in bright sunlight. If artificial light is used, as for color determinations in an office, the light source must be as near the white light of midday as possible. With practice, compensation can be made for the differences. The intensity of incidental light is especially critical when matching soil to chips of low chroma and low value.

Roughness of the reflecting surface affects the amount of reflected light, especially if the incidental light falls at an acute angle. The incidental light should be as near as possible at a right angle. For crushed samples, the surface is smoothed and the state is recorded as "dry, crushed and smoothed."

Guidelines for Recording Color

Uncertainty

Under field conditions, measurements of color are reproducible by different individuals within 2.5 units of hue (one Munsell soil-color chart) and 1 unit of value and chroma. Notations are made to match the chips included on the color charts, typically the nearest whole unit of value and chroma. Soil color should be recorded to the closest color chip provided but not interpolated between chips. For some hues, chips for value of 2.5 are included.

Determinations typically are not precise enough to justify interpolation between chromas of 4 and 6 or between chromas of 6 and 8. Color should never be extrapolated beyond the highest chip. The soil-color charts for individual hues do not show value greater than 8. However, chips with higher values are included on a special "white" chart and should be used for soils with very light colors (e.g., those with a high content of calcium carbonate). Observed colors are always rounded to the nearest chip.

For many purposes, the differences between colors of some adjacent color chips have little significance. For these, color notations have been grouped and named (see fig. 3-14).

Dominant Color

The dominant color is the one that occupies the greatest layer volume. It is always listed first among the colors of a multicolored layer. It is determined using the colors on ped faces or broken peds or on a matrix sample in structureless horizons. If two colors occur, the dominant color makes up more than 50 percent of the volume. If three or more colors are noted, the dominant color makes up more of the layer volume than any other color, although it may occupy less than 50 percent. The expression "brown with yellowish brown and grayish brown" signifies that brown is the dominant color and may, or may not, make up more than 50 percent of the layer.

In some layers, no single color is dominant and the first color listed is not more prevalent than others. The expression "brown and yellowish brown with grayish brown" indicates that brown and yellowish brown make up about equal amounts and are codominant. If the colors are described as "brown, yellowish brown, and grayish brown," the three colors make up nearly equal parts of the layer.

Other Non-Matrix Colors

In addition to either a single dominant matrix color or two or more codominant matrix colors, other non-matrix colors may be present. Non-matrix colors are generally related to one of the following four situations:

1. The additional colors are associated with a ped or void surface feature (such as clay films, silt coatings, slickensides, etc.).
2. The colors are associated with concentrations in the soil (such as plinthite, calcium carbonate, gypsum crystals, etc.).
3. The colors are due to oxidation and/or reduction processes in wet soil (i.e., redoximorphic features, such as iron masses, iron depletions, and manganese nodules).
4. The color is inherited from the parent material and is not the result of pedogenic processes. These colors are *lithochromic* or *lithomorphic* and described as *mottles*.

Protocols for describing redoximorphic features, surface features, and concentrations in the soil (including color) are presented later in this chapter.

Mottling

Mottling refers to repetitive color changes that cannot be associated with compositional properties of the soil. As described above, a color pattern related to a ped surface or other organizational or compositional feature is not mottling. In horizon description, mottle description follows dominant color. Mottles (and other non-matrix features) are described by quantity, size, contrast, color, and, if important, other attributes such as moisture state, shape, and location, in that order.

Quantity is indicated by three areal percentage classes of the observed surface:

Few .... less than 2 percent
Common .... 2 to less than 20 percent
Many.......... 20 percent or more

The notations must clearly indicate the colors to which the terms for quantity apply. For example, "common grayish brown and yellowish brown mottles" could mean that each color makes up 2 to 20 percent of the horizon. By convention, the example is interpreted to mean that the quantity of the two colors *together* is between 2 and 20 percent. If each color makes up between 2 and 20 percent, the description should be "common grayish brown (10YR 5/2) and common yellowish brown (10YR 5/4) mottles."

Size refers to dimensions as seen on a plane surface. If the length of a mottle is not more than two or three times the width, the dimension recorded is the greater of the two. If the mottle is long and narrow, as a band of color at the periphery of a ped, the dimension recorded is the smaller of the two and the shape and location are also described. Five size classes are used to describe mottles:

Fine........................ smaller than 2 mm
Medium .... 2 to less than 5 mm
Coarse.................... 5 to less than 20 mm
Very coarse .... 20 to less than 76 mm
Extremely coarse... 76 mm or more

Contrast refers to the degree of visual distinction that is evident between associated colors. The criteria for determining contrast class are given in table 3-5. The classes for color contrast are:

Faint.—Color is evident only on close examination.
Distinct.—Color is readily seen but contrasts only moderately with the color to which it is compared.
Prominent.—Color contrasts strongly with the color to which it is compared. Prominent colors are commonly the most obvious color feature of the section described.

Contrast is often not a simple comparison of one color with another but is a visual impression of the prominence of one color against a background of several colors.

Mottles and other features (if significant) are described using terms for shape, location, and boundary character.

Shape.—These terms are the same as those used for other concentrations in the soil (i.e., cylindrical, platy, reticulate, etc.).

Table 3-5

Color Contrast Class Terms and Their Criteria

Contrast class	Difference between compared colors			
	Hue	Value		Chroma
Faint*	0;	≤ 2	and	≤ 1
	1;	≤ 1	and	≤ 1
	2;	0	and	0
Distinct*	0;	≤ 2	and	> 1 to < 4
			or	
		> 2 to < 4	and	< 4
	1;	≤1	and	> 1 to < 3
			or	
		> 1 to < 3	and	< 3
	2;	0	and	> 0 to < 2
			or	
		0 to < 2	and	< 2
Prominent*	0;	≥ 4	or	≥ 4
	1;	≥ 3	or	≥ 3
	2;	≥ 2	or	≥ 2
	3			

* If the compared colors have both a value ≤ 3 and a chroma ≤ 2, the contrast is faint, regardless of hue differences.

Location.—The location of the mottles relative to structure of the soil is described.

Boundary classes.—Terms are as follows:

Sharp: Color grades over less than 0.1 mm. Gradation is barely discernable or not discernible by the naked eye, but visible under a 10X lens.

Clear: Color grades over more than 0.1 mm but less than 2 mm. Gradation can be obscure but visible to the naked eye. A 10X lens is not required.

Diffuse: Color grades over 2 mm or more. Gradation is easily discernable by the naked eye. A 10X lens is not required.

Moisture state and physical state of the dominant color are presumed to apply to the mottles unless the description states otherwise. For example, the description of a sample with a specified standard moist broken state may be “brown (10YR 4/3), brown (10YR 5/3) dry; many medium distinct yellowish brown (10YR 5/6) mottles, brownish yellow (10YR 6/6) dry.” Alternatively, the colors in the standard moisture state may be given together, followed by the colors in other moisture states. The color of mottles commonly is given only for the standard state unless colors in another state have special significance.

An example of a description of a sample with a nearly equal mixture of two colors for a moist broken standard state is “intermingled brown (10YR 4/3) and yellowish brown (10YR 5/6) in a medium distinct pattern; brown (10YR 5/3) and brownish yellow (10YR 6/6) dry.” If a third color is present, it can be added, for example, “common medium faint dark grayish brown (10YR 4/2) mottles, grayish brown (10YR 5/2) dry.”

If the mottles are fine and faint and cannot be compared easily with the color standards, the Munsell notation should be omitted. Other abbreviated descriptions are used for specific circumstances.

Color Patterns Within the Soil

Color may be recorded separately for features that merit a distinct description, especially for redoximorphic features but also for peds, concretions, nodules, cemented bodies, filled animal burrows, etc. Color patterns that exhibit a spatial relationship to composition changes or to features, such as nodules or surfaces of structural units, are useful in descriptions because they can infer genesis and soil behavior. Colors may be given for extensions of material from another soil layer. For example, the fine tubular color patterns that extend vertically below the A horizon of some wet soils were determined by the environment adjacent to roots that once occupied the tubules. The relationship of redoximorphic features to locations in the horizon (such as ped faces, ped interiors, pore linings, etc.) provides important clues about internal patterns of wetness. For example, a rim of bright color around an inner zone of lighter color at the surface of some peds relates to water movement into and out of the peds and to oxidation-reduction relationships.

Ground Surface Color

The ground surface color has an important effect on heat transmission into the soil. *Albedo* (the ratio of the reflected incident short-wave solar radiation to the total amount received) is related to soil color, especially *value*. It is an essential parameter for estimating evapotranspiration and for calculating water balance for hydrological models. The color value of the immediate ground surface may differ markedly from that of the surface horizon. For example, raindrop impact that removed clay-sized material from the surface of sand and silt particles may result in a thin surface crust about a millimeter thick with higher color value. Albedo for the fine-earth soil component of the surface cover (given the surface is smooth) can be estimated with the equation:

$$\text{albedo} = 0.069 * (\text{value dry}) - 0.114$$

Specialized studies involving model inputs that include albedo use color information for the total ground surface, including vegetation as well as soil material. In some arid soils, dark rock fragments may have reduced the color value of the ground surface appreciably from that of the fine earth of the surface horizon as a whole. Furthermore, dead vegetation may have color values that differ appreciably from those for the fine earth of the surface horizon. Surface color influences reflectivity of light, which influences the capacity to absorb and release radiant energy.

Soil surface colors at a given site commonly range widely due to the presence of more than one kind of cover. It may be necessary to estimate the areal proportion of the color value for each ground surface type separately (such as rock fragments, dead vegetation, or fine earth), and then select a single color value for each important ground surface component. From the areal proportion of the components and their color value, a weighted average color value for the ground surface may be computed.

Soil Structure

Soil structure refers to units composed of primary particles. Cohesion within these units is greater than the adhesion among units. As a consequence, the soil mass under stress tends to rupture along predetermined planes or zones. These planes or zones form the boundary of the structural units. Compositional differences of the fabric matrix appear to exert weak or no control over where the bounding surfaces occur. If compositional differences control the bounding surfaces of the body, then the term “concentration” is used. The term “structural unit” is used for any repetitive soil body that is commonly bounded by planes or zones of weakness that are not an apparent consequence of compositional differences. A structural unit that is the consequence of soil development is called a *ped*. The surfaces of peds persist through cycles of wetting and drying in place. Commonly, the surface of the ped and its interior have different composition or organization, or both, because of soil development. In contrast to peds, soil-forming processes exert weak or no control on the boundaries of earthy clods. *Clods* commonly form in the surface layer due to the rearrangement of primary particles to a denser configuration through plowing or other mechanical disturbance. The same terms and criteria used to describe structured soils should be used to describe the shape, grade, and size of clods. Commonly, clods have a blocky shape and are large enough to affect tilth adversely. Although the descriptive terms are used for both structural units and clods, this does not infer that clods are the result of pedogenic processes like structural units are. To avoid misunderstanding, the word "clods" is substituted for "structure" in written descriptions (e.g., strong, coarse, angular blocky clods).

Some soils lack structure and are referred to as *structureless*. In structureless layers or horizons, no units are observable in place or after the soil has been gently disturbed, such as after tapping a spade containing a slice of soil against a hard surface or dropping a large fragment of the soil on the ground. When structureless soils are ruptured, coherent soil fragments or single grains, or both, result. Structureless soil material may be either *single grain* or *massive*. In addition to lacking structure, soil material of single grains is loose. On rupture, more than 50 percent of the mass consists of discrete mineral particles.

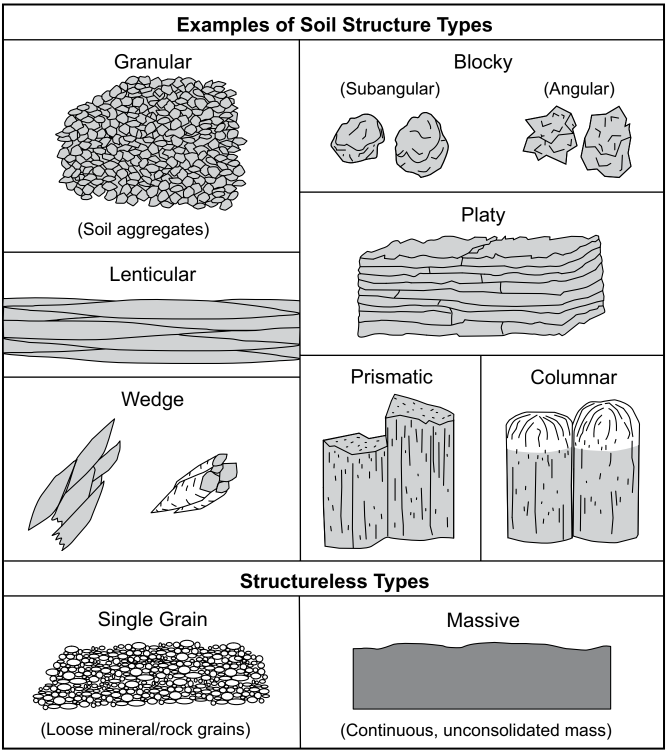
Some soils have *simple structure*, where each unit is an entity without component smaller units. Others have *compound structure*, where large units are composed of smaller units separated by persistent planes of weakness.

In soils that have structure, the shape, size, and grade (distinctness) of the units are described. Field terminology for soil structure has separate sets of terms designating each of the three properties that, when used in combination, form the names for structure. For example, "strong fine granular structure" is used to describe a soil that separates almost entirely into discrete units that are loosely packed, roughly spherical, and mostly between 1 and 2 mm in diameter. The designation of structure by grade, size, and shape can be modified with other appropriate terms to describe other characteristics, e.g., "moderate medium lenticular structure with peds tilted about 15 degrees from horizontal (upslope)." Surface characteristics of units are described separately.

Shape

Several basic shapes of structural units are recognized in soils (fig. 3-16). Supplemental statements about the variations in shape of individual peds are needed in detailed descriptions of some soils. The following terms describe the basic shapes and related arrangements:

Figure 3-16



Examples of soil structure types.

Platy.—The units are flat and platelike. They are generally oriented horizontally.

Prismatic.—The individual units are bounded by flat to rounded vertical faces. Units are distinctly longer vertically, and the faces are typically casts or molds of adjoining units. Vertices are angular or subrounded; the tops of the prisms are somewhat indistinct and normally flat. Figure 3-17 shows a soil profile with prismatic structure in the subsoil.

Columnar.—The units are similar to prisms and bounded by flat or slightly rounded vertical faces. The tops of columns, in contrast to those of prisms, are very distinct and normally rounded.

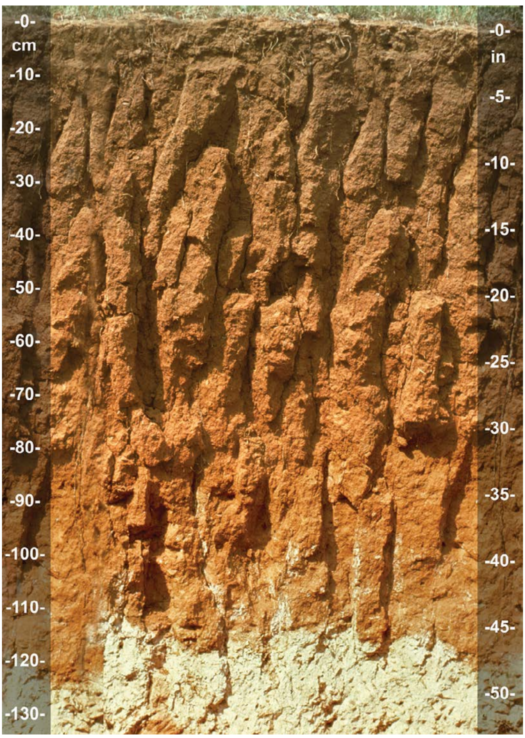
Blocky.—The units are blocklike or polyhedral. They are bounded by flat or slightly rounded surfaces that are casts of the faces of surrounding peds. Typically, blocky structural units are nearly equidimensional but grade to prisms and plates. The structure is described as *angular blocky* (fig. 3-18) if the faces intersect at relatively sharp angles and as *subangular blocky* if the faces are a mixture of rounded and plane faces and the corners are mostly rounded.

Granular.—The units are approximately spherical or polyhedral. They are bounded by curved or very irregular faces that are not casts of adjoining peds.

Wedge.—The units are approximately elliptical with interlocking lenses that terminate in acute angles. They are commonly bounded by small slickensides.

Lenticular.—The units are overlapping lenses parallel to the soil surface. They are thickest in the middle and thin towards the edges. Lenticular structure is commonly associated with moist soils, texture classes high in silt or very fine sand (e.g., silt loam), and high potential for frost action.

Figure 3-17



Prismatic soil structure. (Photo courtesy of John Kelley)

Figure 3-18

Peds with angular blocky structure. (Photo courtesy of John Kelley)

Size

The six size classes are *very fine, fine, medium, coarse, very coarse,* and *extremely coarse.* The extremely coarse class is used only for prismatic, columnar, and wedge-shaped structures. The size limits of the classes differ according to the shape of the units. Table 3-6 gives the size limit classes. The size limits refer to the smallest dimension of plates, lenses, prisms, and columns. For the lens-shaped structures (wedge and lenticular), the measurement is taken at the thickest part of the smallest dimension, not the tapered edges. If the units are more than twice the minimum size of the largest class, the actual size is given, e.g., "moderate very coarse prisms 100 to 150 cm across."

Grade

Grade indicates the distinctness of units. Criteria for grade classes are the ease of separation into discrete units and the proportion of units that hold together when the soil is handled. Three classes are used:

Weak.—The units are barely observable in place. When they are gently disturbed, the disturbed soil material parts into a mixture

Table 3-6

Size Class Terms for Peds with Various Soil Structure Types

Classes	Shape of structure		
	Platy* and granular *(mm)*	Prismatic, columnar, and wedge *(mm)*	Blocky and lenticular* *(mm)*
Very fine	< 1	< 10	< 5
Fine	1 to < 2	10 to < 20	5 to < 10
Medium	2 to < 5	20 to < 50	10 to < 20
Coarse	5 to < 10	50 to < 100	20 to 50
Very coarse	≥ 10	100 to < 500	≥ 50
Extremely coarse	N/A	≥ 500	N/A

* In describing plates, "thin" is used instead of "fine" (i.e., very thin and thin) and "thick" instead of "coarse" (i.e., thick and very thick).

of whole and broken units, the majority of which exhibit no planes of weakness. Faces that indicate persistence through wet-dry cycles are evident if the soil is handled carefully. Distinguishing structureless soils from those with weak structure can be difficult. Weakly expressed structural units in virtually all soil materials have surfaces that differ in some way from the interiors.

Moderate.—The units are well formed and evident in undisturbed soil. When disturbed, the soil material parts into a mixture of mostly whole units, some broken units, and material that is not in units. Peds part from adjoining peds to reveal nearly entire faces that have properties distinct from those of fractured surfaces.

Strong.—The units are distinct in undisturbed soil. They separate cleanly when the soil is disturbed. When removed, the soil material separates mainly into whole units. Peds have distinctive surface properties.

The distinctness of individual structural units and the relationship of cohesion within units to adhesion between units determine grade of structure. Cohesion alone is not specified. For example, individual structural units in a sandy loam A horizon may have strong structure yet be less durable than individual units in a silty clay loam B horizon of weak structure. The degree of disturbance required to determine structure grade depends largely on moisture content and percentage and kind of clay. Only slight disturbance may be necessary to separate the units of a moist sandy loam having strong granular structure, while considerable disturbance may be required to separate units of a moist clay loam having strong blocky structure.

Compound Structure

Smaller structural units can hold together to form larger units. Grade, size, and shape are described for both kinds of units and the relationship of one set to the other is indicated, e.g., "strong medium angular blocks within moderate coarse prisms" or "moderate coarse prismatic structure parting to strong medium subangular blocky."

Extra-Structural Cracks

Cracks are macroscopic vertical planar voids that are much smaller in width than in length and depth. A crack represents the release of strain as a consequence of drying. In contrast to the relatively narrow voids surrounding peds in most soils, the cracks discussed here are the result of localized stress release, which forms planar voids that are wider than the repetitive planar voids normally associated with structural units.

Importance

Cracks, especially large ones, affect water flow into and through the soil, causing it to bypass the soil matrix (bypass flow). They exert significant control on ponded infiltration and hydraulic conductivity, especially if they extend to (or close to) the surface. Cracks are generally associated with soils that are subject to pronounced shrinking and swelling. They can indicate potential engineering hazards to homes, roads, and other structures. For taxonomic purposes, the width and depth of cracks as well as their temporal open-close cycles have importance. The areal percentage of such cracks, either on a vertical exposure or on the ground surface, can be measured by line-intercept methods.

Kinds of Cracks

Cracks are characterized as either *crust-related* or *trans-horizon*. Crust-related cracks are shallow cracks that initiate at the surface and are restricted to a surface crust layer. They form primarily from raindrop impact and soil puddling followed by drying and consolidation.

Trans-horizon cracks commonly extend across more than one horizon. They may extend upward to the soil surface and downward to significant depth. These cracks are commonly associated with soils that have a high content of smectitic clay minerals. They open as the soil dries out and close upon rewetting. Less commonly, some trans-horizon cracks form upon dewatering and subsequent consolidation of poorly drained sediments with high *n* value (fluid materials), e.g., upon drainage of some soils that are classified as Hydraquents. Once formed, these cracks do not open and close seasonally but rather remain open permanently.

Crust-related cracks.—Two kinds of crust-related cracks are recognized: reversible and irreversible.

Surface-initiated reversible crust-related cracks form as a result of drying from the surface downward. They close after relatively slight surficial wetting and have little influence on ponded infiltration rates. These cracks tend to be very shallow (less than about 0.5 cm) and are transient (i.e., close upon wetting).

Surface-initiated irreversible crust-related cracks form as a result of the near-surface water reduction in material with an exceptionally high water content, commonly from frost action. These cracks tend to be shallow (between about 0.5 and 2 cm) and seasonally transient. The cracks may not close completely when rewet and extend through the crust. They increase ponded infiltration rates, but only to a small degree.

Trans-horizon cracks.—Two kinds of trans-horizon cracks are recognized: reversible and irreversible.

Subsurface-initiated reversible trans-horizon cracks form as a result of appreciable reduction in water content from field capacity in horizons or layers with considerable extensibility (fig. 3-19). They close in a period of days if the horizon is brought to the *moderately moist* or wetter state. They extend upward to the soil surface unless there is a relatively thick overlying horizon that is very weakly compacted (loose or very friable) and does not permit the propagation of cracks. These cracks greatly influence ponded infiltration rates, hydraulic conductivity, and evaporation.

Subsurface-initiated irreversible trans-horizon cracks are the permanent cracks described in *Soil Taxonomy* (as described for soil families). They have a similar origin to surface-initiated irreversible cracks, although quite different agencies of formation are involved. Rather than forming due to shrinkage of the surface layer upon air drying, these cracks form due to subsoil drainage and subsequent consolidation of some very fluid soils.

Figure 3-19

Large reversible trans-horizon cracks extend from the soil surface deep into the subsoil of this clayey soil, which is classified as a Vertisol.

Descriptions of Cracks

Descriptions of cracks include:

Relative frequency.—Average number of cracks per square meter.
Depth.—Average depth of penetration.
Kind.—Reversible crust-related, irreversible crust-related, reversible trans-horizon, or irreversible trans-horizon.

If the cracks do not extend to the surface, this should be noted. Examples of crack descriptions: "On average, five reversible trans-horizon cracks per square meter extend from the surface to about 50 cm" and "on average, five reversible trans-horizon cracks per square meter beginning below 18 cm extend to about 50 cm."

Internal Ped and Void Surface Features

Features formed by pedogenic processes commonly occur on or beneath ped or void surfaces. Such features include: (1) coats of various substances covering part or all of surfaces, (2) material concentrated on surfaces due to preferential removal of finer material, (3) stress formations in which thin layers at the surfaces have undergone particle reorientation or packing by stress and/or shear, and (4) material infused beneath surfaces (termed a “hypocoat”). All these features differ from the adjacent material in composition, orientation, and/or packing. *Hypocoats* commonly result from oxidation and reduction processes and are generally described as redoximorphic features (discussed below).

Description of surface features may include kind, location, amount, and distinctness. Color, texture, and other characteristics may also be described, especially if the features contrast strongly with characteristics of adjacent material.

Kinds

Surface features are distinguished by differences in texture, color, packing, particle orientation, or reaction to selected tests. If a feature is distinctly different from the adjacent material but its kind cannot be determined, it is still described.

Clay films.—Thin layers of oriented, translocated clay; also called clay skins or argillans (fig. 3-20).

Clay bridges.—Illuvial clay linking together adjacent mineral grains (fig. 3-21).

Figure 3-20

Shiny clay films coat the surface of this ped. (Photo courtesy of John Kelley)

Figure 3-21

Sand grains (visible as individual quartz grains) coated and bridged with illuvial clay (smooth yellowish color). (Photo courtesy of John Kelley)

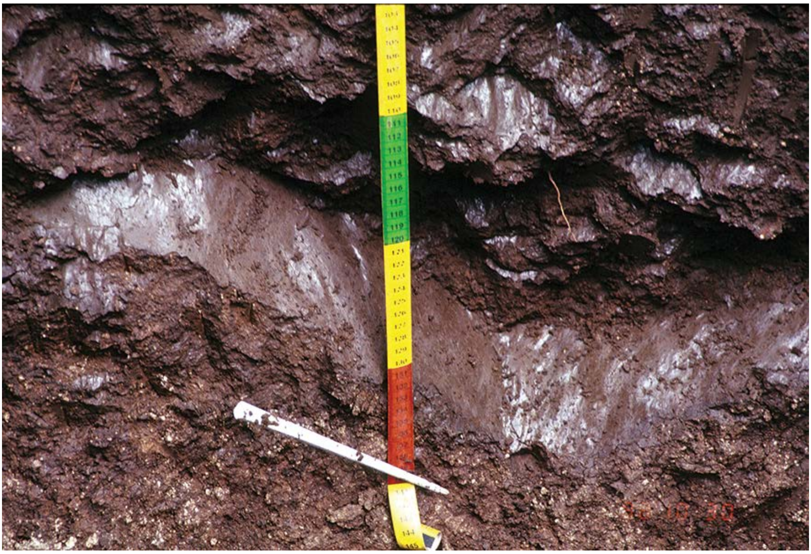
Sand or silt coats.—Sand or silt grains adhering to a ped, void, or crack surface. The grains may be derived from material originally in a horizon from which finer particles have been removed. These coats are also referred to as *skeletans.* Sand or silt coats may also form by translocation and deposition of sand or silt from upper horizons or via oxidation-reduction reactions that preferentially remove iron and/or manganese and, in some cases, clay. Coats inferred to form from oxidation-reduction reactions are described as redoximorphic features.

Other coats.—Coats composed of iron, aluminum, or manganese oxides; organic matter; salts; or carbonates. They are described by properties that can be observed in the field. Laboratory analyses may be needed for verification.

Stress surfaces.—Pressure faces, also referred to as *stress cutans*. These surfaces are smoothed or smeared. They form through rearrangement caused by shear forces. They may persist through successive drying and wetting cycles. Although similar in appearance to clay films, pressure faces can be distinguished by sand grains that protrude slightly above the surface and are not coated with clay.

Slickensides.—Stress surfaces that are polished and striated (fig. 3-22). They typically have dimensions exceeding 5 cm. They are produced when a relatively large volume of soil slides over another. They are common below a depth of 50 cm in swelling clays (clays subject to large changes in water state). Slickensides associated with structural surfaces resulting from pedogenesis are considered *pedogenic* in nature. Those associated with faults or mass soil movement are considered *geogenic*.

Figure 3-22



Prominent slickensides in the Bss horizon of a Vertisol.

Location

Various surface features may occur on some or all structural units, channels, pores, primary particles or grains, soil fragments, rock fragments, or pararock fragments. The kind and orientation of the surface on which features are observed are always described (e.g., "clay films are on vertical but not horizontal faces of peds").

Amount

The percentage of the total surface area occupied by a particular surface feature over the extent of the horizon or layer is described.

Amount can be characterized using the following classes:

Very few .... less than 5 percent
Few .... 5 to less than 25 percent
Common .... 25 to less than 50 percent
Many................ 50 to less than 90 percent
Very many........ 90 percent or more

These classes are also used to describe the amount of bridges connecting particles. This amount is based on the percentage of particles of a designated size that are joined to adjacent particles of similar size by bridges at contact points.

Distinctness

Distinctness refers to the ease and degree of certainty with which a surface feature can be identified. It is related to thickness, color contrast with the adjacent material, and other properties. However, it is not itself a measure of any one of them (e.g., some thick coats are faint and some thin coats are prominent). The distinctness of some surface features changes markedly as water state changes. The classes of distinctness are:

Faint.—Feature is evident only on close examination with 10X magnification and cannot be identified positively in all places without greater magnification. The contrast with the adjacent material in color, texture, and other properties is minimal.

Distinct.—Feature can be detected without magnification, although magnification or tests may be needed for verification. The feature contrasts enough with the adjacent material that differences in color, texture, or other properties are evident.

Prominent.—Feature is conspicuous without magnification when compared to a surface broken through the soil. Color, texture, or other property or a combination of properties contrasts sharply with properties of the adjacent material, or the feature is thick enough to be conspicuous.

The typical order of description is: amount, distinctness, color, texture, kind, and location. For example: “few distinct grayish brown (10YR 5/2) clay films on vertical faces of peds” or “many distinct brown (10YR 4/3) clay bridges between mineral grains.” Only properties that add to the understanding of the soil are listed. If texture of the surface feature is obvious, as in most stress surfaces, it is not described. Kind and location are needed for all features identified. Volume, if important, is estimated separately.

Concentrations

Concentrations are identifiable bodies within the soil that form and accumulate due to pedogenesis. Pedogenic processes responsible for concentration development in the soil include chemical dissolution and precipitation, oxidation/reduction, and accrual due to physical or biological processes. Some concentrations are thin and sheet-like, some are nearly equidimensional, and others have irregular shapes. They may contrast sharply with the surrounding material in strength, composition, or internal organization, or their differences with the surrounding material may be slight. Rock and pararock fragments or inherited minerals (such as pockets of mica flakes) are not considered concentrations.

Kinds

Masses are non-cemented concentrations that commonly cannot be removed from the soil as a discrete unit. Masses may consist of, but are not limited to, calcium carbonate (fig. 3-23), fine crystals of gypsum or soluble salts, or iron and manganese oxides. In most cases, masses form in place.

Plinthite consists of reddish, iron-enriched bodies that have a low content of organic matter. In contrast to most other masses, plinthite bodies are coherent enough to be separated readily from the surrounding soil.

Plinthite commonly occurs within and above reticulately mottled horizons (fig. 3-24). It has higher penetration resistance than adjacent brown or gray bodies or than red bodies that do not harden. Soil layers that contain plinthite rarely become dry in their natural setting. Plinthite bodies are commonly about 5 to 20 mm across their smallest dimension. They are *firm* or *very firm* when moist, *hard* or *very hard* when air dry, and *moderately cemented* on repetitive wetting and drying, especially when exposed to sunlight (e.g., in road banks and gully walls).

Upon repeated wet-dry cycles, plinthite may irreversibly harden and convert to indurated ironstone. Plinthite bodies commonly occur as discrete nodules or plates. The plates are oriented horizontally. The nodules occur above, and the plates within, the upper part of the reticulately mottled horizon. The plates generally have a uniformly reddish color and have sharp boundaries with the surrounding brown or gray material. The part of the iron-rich body that is not plinthite normally stains the fingers if rubbed while wet, but the plinthite center does not. Plinthite has a harsh, dry feel when rubbed, even if wet. Horizons

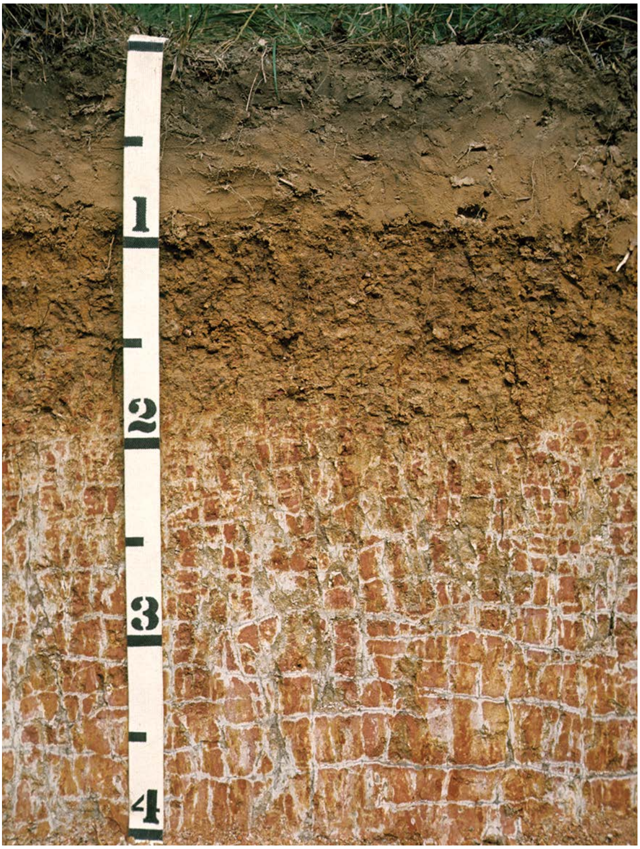
Figure 3-23

Masses of secondary calcium carbonate (white bodies below a depth of about 60 cm) in the calcic horizon of an Aridisol.

containing plinthite are more difficult to penetrate with an auger than adjacent horizons at the same water state and with the same clay content. Plinthite generally becomes less cemented after prolonged submergence in water. An air-dried sample can be dispersed by normal procedures for particle-size distribution.

Ironstone is an iron-oxide concentration that is at least weakly cemented. Ironstone nodules commonly occur in layers above plinthite. They are thought to be plinthite that has cemented irreversibly because of repeated wet-dry cycles. Commonly, the center of iron-rich bodies cement upon repeated wetting and drying while the periphery does not.

Figure 3-24



A soil in which a reticulately mottled zone with plinthite (darkest red colors) is below a depth of about 2 feet.

Nodules and **concretions** are cemented bodies of various shapes that can be removed from the soil intact and do not slake in water. They do not have a crystal structure discernable by field observation (10X lens). Concretions differ from nodules by internal organization. They possess a crude internal symmetry organized around a point, a line, or a plane. The internal structure typically takes the form of concentric layers that are visible to the naked eye. A coat or a thin outer layer of an otherwise undifferentiated body does not indicate a concretion. Nodules, by contrast, lack evident internal organization.

Crystals are macro-crystalline forms of relatively soluble salts that form in place. They may occur singly or in clusters (fig. 3-25). Gypsum,

Figure 3-25

A cluster of gympsum crystals (selenite) in an Aridisol.

calcite, halite, and other salt crystals are common in arid and semiarid soils. Crystals composition should be denoted if known.

Finely disseminated materials are small precipitates dispersed throughout the matrix. The material is not observable with the naked eye but can be detected by chemical reactions (e.g., effervescence of calcium carbonate with dilute HCl). An example is calcium carbonate that has accrued due to dust fall and its subsequent dissolution and re-precipitation throughout the matrix of a horizon.

Biological concentrations are discreet bodies accumulated by biological process. Examples include fecal pellets and wormcasts.

Inherited minerals consist of distinct, observable mineral particles in the soil that formed from geologic rather than pedogenic processes. Mica flakes and glauconite pellets are examples.

Describing Concentrations Within the Soil

Concentrations within the soil may have several important attributes, including number or amount, size, shape, consistence, color, composition, kind, and location. Not all attributes are necessarily described. The order as listed above is convenient for describing them, e.g., "many, fine, irregular, hard, light gray (10YR 7/1) carbonate nodules distributed uniformly through the horizon." Descriptions for kind have already been discussed in this section, and those for consistence and color are discussed in other parts of this chapter.

Amount or **quantity** of concentrations refers to the relative volume of a horizon or other specified unit occupied by the bodies. The classes are the same as those used for quantity of redoximorphic features and mottles:

Few .... less than 2 percent
Common .... 2 to less than 20 percent
Many.......... 20 percent or more

Size may be measured directly or designated by a class. The dimension to which size-class limits apply depends on the shape of the body described. If the body is nearly uniform, the shortest dimension is measured, such as the effective diameter of a cylinder or the thickness of a plate. For irregular bodies, the longest dimension is measured (if needed, more measurements can be given for clarification). The classes are the same as those used for mottles and redoximorphic features:

Fine........................ less than 2 mm
Medium .... 2 to less than 5 mm
Coarse.................... 5 to less than 20 mm
Very coarse .... 20 to less than 76 mm
Extremely coarse ... 76 mm or more

Shape of concentrations varies according to kinds of concentrations and commonly within a concentration. (Shape terms are generally not used to describe crystals, however, because the crystal type itself implies its shape.) The terms for concentration shape are:

Cubic.—Roughly equidimensional, blocklike structures.

Cylindrical.—Cylindrical or tubular shape; one dimension is greater than the other two.

Dendritic.—Branched, elongated, tubular forms.

Irregular.—Concentrations characterized by nonrepeating spacing or shape, but not elongated (as a dendritic form).

Lenticular.—Roughly disk-shaped forms, thickest in the middle and thinning toward the edges.

Pendular.—Coatings or nodules formed on the undersides of rock fragments.

Platy.—Shaped like a plate; one dimension is much smaller than the other two.

Reticulate.—Crudely interlocking structures (common with some plinthite concentrations).

Rosettelike.—Interlocking blade-like structures forming a petal-like structure.

Spherical.—Approximately equidimensional and well rounded.

Threadlike.—Thin, elongated filament-like structures (but not dendritic).

Composition of bodies (calcium carbonate, iron-manganese, gypsum, etc.) is described if known and if important for understanding their nature or the nature of the soil in which they occur. Some of the physical attributes of the interior of a feature are implied by the name. Other features, such as enclosed mineral grains, patterns of voids, or similarity to the surrounding soil, may be important.

A distinction is made between bodies composed dominantly of a single substance and those composed of earthy material impregnated by various substances. For many bodies, the chemical composition cannot be determined with certainty in the field. If the substance dominates the body, then the body is described as a substance body (durinode nodules, carbonate concretions, salt crystals, etc.). If the substance impregnates other material, the body is described as a body of substance accumulation (carbonate masses, gypsum masses, plinthite, etc.).

Carbonates and iron commonly dominate or impregnate nodular or concretionary bodies. Discrete nodules of clay occur in some soils; argillaceous impregnations are less common. Materials dominated by manganese are rare; manganese is conspicuous in some nodules that have a high content of iron, called "iron-manganese nodules." Crystals are commonly calcite, gypsum, and other salts (such as sodium chloride) and less commonly barite, selenite, or satin spar. Some concentrations have biological sources, such as fecal pellets and wormcasts.

Pedogenic Carbonates

Carbonates that have translocated within the soil and subsequently precipitated in place from the soil solution are considered to be pedogenic. They are not simply inherited from the parent material. They are the same as "identifiable secondary carbonates" discussed in *Soil Taxonomy*.

Forms of Carbonate Accumulation

The term "forms" refers to the outward expression of bodies of pedogenic carbonate accumulations. Carbonate itself exists as crystals, predominantly calcite ($CaCO_3$), in the size range of fine silt to coarse clay (approximately 10 to 1 μm). These crystals precipitated on the surfaces of rocks, sand, and silt particles or in association with roots and microorganisms. With time, carbonate crystals accumulate within the soil fabric and are visible as:

Filaments.—Threadlike concentrations of carbonate typically < 1 mm in diameter and a few centimeters long.

Root casts.—Branching (and commonly tubular) forms of carbonate accumulation (carbonate pseudomorphs of roots).

Bands.—Sheet-like deposits of carbonate typically ranging from about 1 to several millimeters thick. They form along the bedding planes of finely stratified parent material and are separated by soil with little or no macroscopic carbonate.

Joint fillings.—Vertical bands of carbonate in the fracture planes of large prisms in soil. Joint fillings, in profile, range from less than 1 to a few centimeters in width.

Coatings.—Deposits of carbonate on the surfaces of rock fragments and sand grains. They may be continuous or discontinuous and have a rupture resistance ranging from non-cemented to extremely weakly cemented.

Pendants.—Deposits of laminar carbonate coatings on rock that are very weakly cemented to indurated. They are more common on the bottom of rocks than on the top. They commonly have stalactite-like protrusions radiating perpendicularly away from the rock fragment.

Masses.—Bodies of carbonate accumulation of various shapes that are non-cemented or extremely weakly cemented and cannot be removed as discrete units from soil.

Nodules.—Rounded bodies of carbonate accumulation that are very weakly cemented to indurated and can be removed as discrete units from soil.

Concretions.—Rounded bodies of carbonate accumulation that are very weakly cemented to indurated. They have spherically concentric layers surrounding a nucleus.

Cylindroids.—Cylindrical bodies of carbonate accumulations that are very weakly cemented to indurated. Many are cicada casts impregnated with calcium carbonate while others developed in soil material filling former root channels or small krotovinas. Cylindroids are typically less than 2.5 cm thick. They are typically vertical but may also be diagonal or horizontal.

Beds.—Carbonate accumulations along bedding planes of parent material that are similar to bands but differ in size (ranging from a few centimeters to a meter or more thick). They range from non-cemented to indurated, occur below the main zone of pedogenic horizons, and preserve the original sedimentary structure.

Plugged horizons.—Pedogenic carbonate accumulations that occur at the soil-horizon-landscape scale, which is larger than the soil-profile scale, at which filaments, nodules, and other carbonate forms occur. They are characterized by laterally continuous pedogenic carbonate that has engulfed soil particles, filled most or all pores, and obliterated the original sedimentary structure. Most plugged horizons are strongly cemented to indurated, although some are non-cemented.

Laminar horizons.—Smooth, strongly cemented to indurated deposits of carbonate that develop on top of plugged horizons (or shallow bedrock). They have a fabric that contains much more carbonate than the underlying plugged horizon and essentially no allogenic skeletal grains.

Laminae.—Thin (less than 1 mm to a few millimeters) individual layers of carbonate comprising the laminar horizon. They typically parallel one another, but one set may truncate another set at various angles.

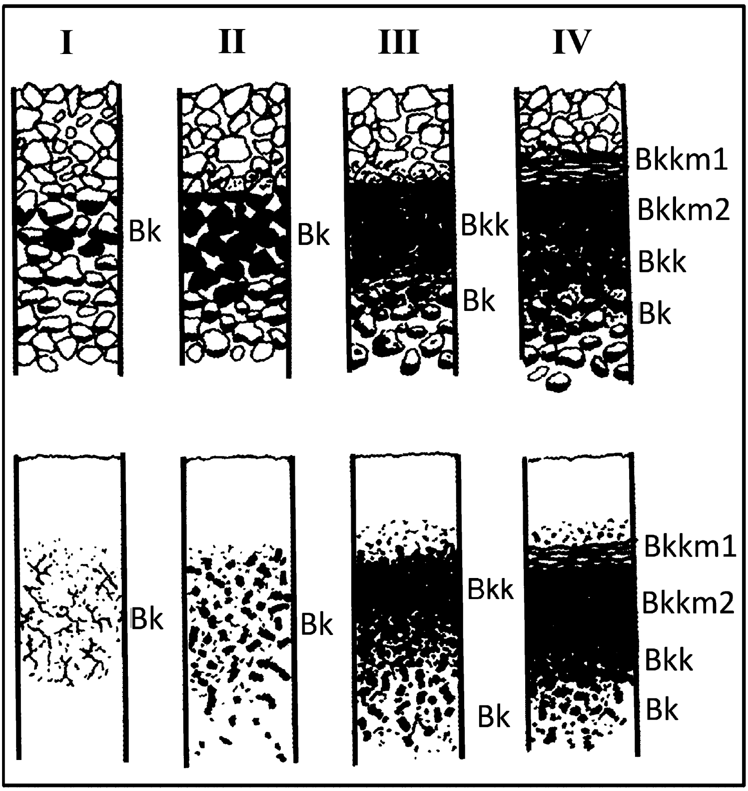
Pisoliths.—Subangular to spheroidal carbonate masses (2 to more than 100 mm in diameter) that form within highly developed petrocalcic horizons. They are characterized by concentric banding and an internal structure of disrupted laminae or by disrupted concentric banding that may or may not have detrital material at the core.

Ooliths.—Spheroidal carbonate masses (less than 2 mm in diameter) that form within highly developed petrocalcic horizons. They have an internal structure of laminae that may or may not have detrital material at the core.

Stages of Carbonate Accumulation

Pedogenic carbonate that forms in soils in arid and semiarid climates is closely linked to age (i.e., progressively older geomorphic surfaces have soils with commensurately greater amounts of carbonate). Gile et al. (1966) described carbonate accumulation through four successive morphogenic stages with a distinction between gravelly and nongravelly soils (fig. 3-26). Soils that form in *gravelly parent materials* progress from pebble coatings (Stage I) to interpebble fillings (Stage II), a plugged horizon (Stage III), and eventually a laminar horizon atop the plugged horizon (Stage IV). Soils that form in *nongravelly parent materials* progress from filaments (Stage I) to nodules (Stage II), a plugged horizon (Stage III), and eventually a laminar horizon atop the plugged horizon (Stage IV). Bachman and Machette (1977) and Machette (1985) recognized two additional stages. Stage V is characterized by laminae less than 1 cm thick and may contain pisoliths as well as vertical faces and fractures coated with laminated carbonate. Stage VI is characterized by multiple generations of recemented laminae, breccia, and pisoliths. The time required to reach a certain morphogenetic stage depends on soil particle size and quantity of carbonate inputs. Gravelly soils pass through the stages more quickly than nongravelly soils because they have less surface area and less total pore space. Pedogenic carbonate that forms above the phreatic zone by means of capillary rise does not necessarily proceed through the morphogenetic stages.

Figure 3-26



Schematic diagram of diagnostic carbonate morphology for the four main stages of carbonate accumulation in two morphogenetic sequences (Gile et al., 1966).

Redoximorphic Features

Redoximorphic features (RMF) include color patterns, mineral concentrations, and a reduced (in respect to iron) soil state that form via coupled oxidation/reduction reactions involving iron and manganese under anaerobic soil conditions. Saturation or near saturation limits oxygen diffusion in soil. Microbial activity consumes existing oxygen, and an anaerobic condition results. Under anaerobic conditions, certain microbes utilize chemical species other than oxygen as the terminal electron acceptor for carbon metabolism. Such microbially mediated redox processes follow a sequence based on electrochemical or redox potential, which is a measure of anaerobic intensity. The metabolic energy gain for an organism is the energy difference between reduced carbon and the specific electron acceptor. The oxidant with the highest redox potential is utilized first, followed by the oxidant with the next highest potential. The favorability order for electron acceptors in soil is:

$$O_2 > NO_3^{2-} > Mn\ (VI) > Fe\ (III) > SO_4^{2-} > CO_2 > H^+$$

Iron (Fe), and to a lesser extent manganese (Mn), serve as soil color pigments. Thus, oxidation and reduction of these species results in color variations and/or concentrations indicative of soil wetness. Reduced iron, Fe(II), and manganese ions are mobile in soil compared to their oxidized state. They are subject to leaching or migration from higher concentration (an anaerobic zone, such as a ped interior) to lower concentration (aerobic zone, such as a ped surface). Upon oxygen exposure (higher redox potential), reduced species become oxidized and immobile and form iron and manganese concentrations, which commonly are redder than the adjacent matrix. Areas that lose iron or manganese are pigment depleted (redox depletions) and have a grayer or lighter color due to the clean, exposed mineral surface. Depletions of chroma 2 or less are key morphological indicators of seasonal or periodic saturation. It is important to note that depletions form via iron or manganese reduction while concentrations form via iron or manganese oxidation.

Chemical and physical soil properties influence oxidation-reduction reactions. Thus, RMF formation may not occur in saturated soils in certain settings. For example, higher pH decreases the electron-accepting tendency of a chemical species so that RMF formation is less likely in alkaline soils. Similarly, because cold temperature reduces microbial activity, RMF may not form during winter months even though the soil is saturated. Moreover, oxidation/reduction reactions may not produce visually observable RMF, such as in red soil parent materials or horizons in which organic matter controls soil color.

Once formed, iron-oxide concentrations are stable in an oxidized soil and depletions remain pigment-free. Thus, some RMF may be relict in that they formed under an anaerobic condition that no longer exists. For example, a stream terrace that currently lacks internal wetness due to stream downcutting may retain RMF formed when a water table existed at a higher position in the soil. If proven relict, RMF can be described as such. Redoximorphic features in anthropologically drained soils are not considered relict because original conditions can be restored.

Describing Redoximorphic Features

Because RMF have a strong relationship to soil wetness, they are typically described separately from other color variations or concentrations. Mottles (color variations not due to iron loss or accrual, such as variegated weathered rock) are described with soil color. The characteristics routinely described for RMF include quantity, size, contrast, color, kind, and location. If important, the moisture state, shape, hardness, and boundary can also be described. Guidelines for describing color and the associated moisture state are the same as those for recording color (see previous section). Terms for describing hardness of cemented redox concentrations are given in the section "Rupture Resistance" below (cementation classes). Terms for describing quantity, size, contrast, color, and location of RMF are the same as those for describing concentrations within the soil (see section above). Kinds of RMF are discussed below.

Redox Concentrations

Redox concentrations are localized accretions of Fe and/or Mn, which may occur as cemented nodules or amorphous phases, that result in enhanced pigmentation and/or a cemented precipitate. Generally, concentrations form through iron oxidation from Fe(II) to Fe(III), which yields a color redder than that of the adjacent matrix (fig. 3-27). In strongly reducing conditions, however, ferrous iron [Fe(II)] may accrete, especially in the presence of S, forming a concentration that is black or blue gray in color. Redox concentrations have the following forms:

Masses.—Non-cemented bodies or localized regions of enhanced pigmentation due to Fe and/or Mn accretion. Masses that occur as coatings or thin matrix impregnations along pores (such as root channels) are referred to as pore linings.

Nodules or concretions.—Cemented bodies of iron-manganese oxides that formed through successive wet-dry cycles. (See the discussion of concentrations above for more detail).

Figure 3-27

Redoximorphic features that consist of a redox concentration, as an iron mass (reddish area along ped surface) and an iron depletion (light-colored area surrounding the root channel in ped interior). (Photo courtesy of John Kelley)

Redox Depletions

Redox depletions are localized zones of decreased pigmentation due to a loss of iron or manganese, with or without clay loss. The pigment loss produces a color grayer, lighter, or less red than that of the adjacent matrix (fig. 3-27). The pigment loss reveals the underlying mineral color. Redox depletions have a hue that is yellower, greener, or bluer than that of the adjacent matrix and/or a higher value and/or a lower chroma. Redox depletions include, but are not limited to, what were previously called "low chroma mottles" (chroma < 2), which are key indicators of seasonal or periodic soil saturation. Redox depletions occur in the following forms:

Iron depletions.—Localized zones that have lost iron and/or manganese pigment due to oxidation or reduction reactions under anaerobic conditions but that have a clay content similar to that of the adjacent matrix.

Clay depletions.—Localized zones that have lost iron, manganese, and clay. These features are commonly referred to as *silt coatings* or *skeletans.* Silt coatings may form by eluvial processes rather than from oxidation and reduction. Soil features of inferred eluvial origin (for example, albic materials, silt coatings, and skeletans) are not considered or described as a redox depletion.

Reduced matrix.—A soil horizon, layer, or zone that is reduced in respect to iron. It has an *in situ* matrix chroma ≤ 2 and/or a hue of 5GY, 5G, or 5BG that reflects the presence of Fe(II). The color of a soil sample becomes visibly redder or brighter (oxidizes) when exposed to air. The color change typically occurs within 30 minutes. A 0.2% solution of alpha,alpha-dipyridyl dissolved in 1N ammonium acetate (NH_4OAc) pH 7 can verify the presence of Fe^{+2} in the field (Childs, 1981).

Consistence

Soil consistence in the general sense refers to the soil material's degree of cohesion and adhesion or resistance to deformation or rupture. As described here, consistence includes: (1) resistance of soil material to rupture, (2) resistance to penetration, (3) plasticity, toughness, and stickiness of puddled soil material, and (4) the manner in which the soil material behaves when subject to compression. Although several tests are described, only those which may be useful should be applied. In addition to descriptions of soil consistence, this section discusses the classes for excavation difficulty, which is reflective of the consistence properties of the soil.

Consistence is *not* synonymous with consistency. Originally, consistency was used in soil engineering to define degree of resistance to penetration by thumb or thumbnail (test designation D 2488, ASTM, 2011). The engineering term was generalized for use in soil survey and called "consistence." The set of tests to determine consistency, however, is different from those for consistence. Consistence is highly dependent on the soil water state and the description has little meaning unless the water state class is specified or is implied by the test. For rupture resistance, separate class terms are provided for tests on dry soil (moderately dry or very dry soil water states) and moist soil (slightly dry through satiated soil moisture states). To determine cementation class, the sample is air dried, then submerged in water for at least 1 hour, and checked for slaking. Stickiness, plasticity, and toughness tests are performed on puddled soil material. Stickiness determinations are made at the highest moisture content, when the sample is most sticky. Tests for manner of failure are best performed on moderately moist or wetter samples. Penetration resistance depends strongly on moisture state, which should always be noted.

The class definitions for rupture resistance and toughness include both qualitative descriptions as well as quantitative limits for the stress or force applied to the sample. Since the perception of the relative amount of force required to cause a sample to fail varies by individual, one should learn what the various classes of applied force feel like personally. The tactile sense of the class limits may be learned by applying force to top-loading scales and sensing the pressure through the tips of the fingers or through the ball of the foot. Postal scales may be used for the resistance range testable with the fingers. A bathroom scale may be used for higher rupture resistance. To calculate force in newtons, multiply kg by 10, or pounds by 4.54. One joule is equal to the energy delivered by dropping a 1-kg weight from a height of 10 cm. (The 3 joules class limit is approximately equivalent to dropping a 2-pound weight from a height of 1 foot). An easy to develop training tool for calibrating one's fingers to estimate applied force is to record the force required to compress springs with varying degrees of resistance using scales as described above. A set of small springs that approximate the class limits for rupture resistance classes can then be used as "known samples" for estimating rupture resistance and toughness classes. For determinations on the natural fabric, variability among specimens is likely to be large. Multiple measurements may be necessary. Recording median values helps reduce the influence of the extremes measured.

Rupture Resistance for Blocklike Specimens

Table 3-7 shows the classes of resistance to rupture and the means of determination for specimens that are blocklike. Different class sets are provided for moderately dry and very dry soil material and for slightly dry and wetter soil material. Unless otherwise specified, the soil water state is assumed to be that indicated for the horizon or layer when described. Cementation is an exception. To test for cementation, the specimen is air dried and then submerged in water for at least 1 hour. Cemented materials will resist slaking. Cementation class placements do not pertain to the soil material at the field water state.

The blocklike specimen should be 25 to 30 mm on edge. Direction of stress relative to the in-place axis of the specimen is not defined unless otherwise indicated. The specimen is compressed between the extended thumb and forefinger, between both hands, or between the foot and a nonresilient flat surface. If the specimen resists rupture by compression, a weight is dropped onto it from increasingly greater heights until rupture. Failure is at the initial detection of deformation or rupture. Stress applied in the hand should be for a period of 1 second.

Specimens of standard size and shape are not always available. While large blocks can be trimmed to the standard size, smaller blocks cannot. Blocks of specimens that are smaller than 25 to 30 mm on edge may still be tested, but the observed force required for rupture needs to be adjusted to approximate what would be expected if the block were the standard size. The force withstood may be assumed to decrease as the reciprocal of the dimension along which the stress is applied. For example, if a moist block specimen with a length of 10 mm along the direction the force is applied ruptures at 4 N stress, the following equation can be used to adjust the observed stress at failure to that for a standard 28-mm block:

Adjusted stress value =
[(28 mm/actual cube length mm)^2 x observed stress (N) at failure]

For the 10-mm specimen in the example above, [(28/10)^2 x 4 N] equals an adjusted stress of about 31 N. According to table 3-7, the rupture resistance class is firm.

Soil structure complicates the evaluation of rupture resistance. If a specimen of standard size can be obtained, rupture resistance of the standard specimen is reported. Other individual constituent structural units can also be described. Typically, the constituent structural units must exceed about 5 mm in the direction of applied stress. Expression must exceed weak for the rupture resistance of the individual structural units to be evaluated.

If structure size and expression are such that a specimen cannot be obtained, then the soil material overall is loose. Structural unit resistance to rupture may be determined if the size is large enough (exceeds about 5 mm in the direction of applied stress) for a test to be performed. Soils with moderate or strong structure and structural units that are less than 5 mm in the direction of applied stress are considered very friable or loose.

Table 3-7

Rupture Resistance Classes for Blocklike Specimens

Classes			Test description	
Moderately dry and very dry	**Slightly dry and wetter**	**Air dried, submerged**	**Operation**	**Stress applied***
Loose	Loose	Not applicable	Specimen not obtainable	
Soft	Very friable	Non-cemented	Fails under very slight force applied slowly between thumb and forefinger	< 8 N
Slightly hard	Friable	Extremely weakly cemented	Fails under slight force applied slowly between thumb and forefinger	8 to < 20 N
Moderately hard	Firm	Very weakly cemented	Fails under moderate force applied slowly between thumb and forefinger	20 to < 40 N
Hard	Very firm	Weakly cemented	Fails under strong force (maximum of about 80 N) applied slowly between thumb and forefinger	40 to < 80 N
Very hard	Extremely firm	Moderately cemented	Cannot be failed between thumb and forefinger but can be between both hands or by placing on a nonresilient surface and applying gentle force underfoot	80 to < 160 N

Table 3-7.—continued

Classes			Test description	
Moderately dry and very dry	**Slightly dry and wetter**	**Air dried, submerged**	**Operation**	**Stress applied***
Extremely hard	Slightly rigid	Strongly cemented	Cannot be failed in hands but can be underfoot by full body weight (about 800 N) applied slowly	160 to < 800 N
Rigid	Rigid	Very strongly cemented	Cannot be failed underfoot by full body weight but can be by blow of < 3 J	800 N to < 3 J
Very rigid	Very rigid	Indurated	Cannot be failed by blow of < 3 J	≥ 3 J

* Both force (newtons; N) and energy (joules; J) are employed. The number of newtons is 10 times the kilograms of force. One joule is the energy delivered by dropping a 1 kg weight 10 cm.

Rupture Resistance for Plate-Shaped Specimens

The following procedure is used to determine rupture resistance for plate-shaped specimens, such as surface crusts, peds with platy or lenticular structure, and similar plate-shaped specimens for which the length and width are several times more than the thickness. The specimen should be 10 to 15 mm on edge. It should be about 5 mm thick, or the thickness of occurrence if less than 5 mm. For surface crusts, the thickness includes the crust proper and the soil material adhering beneath it. For some crusts with closely spaced cracks, however, the specimens may be too small to make the test applicable. The specimen is grasped on edge between extended thumb and forefinger. Force is applied along the longest of the two principal dimensions. Table 3-8 lists the classes and their criteria. Compression to failure should be about 1 second in duration.

For calibration of finger force applied with the quantitative class limits, a scale may be used to both rupture the specimens directly and develop the finger tactile sense. Force is applied with the forefinger through a bar 5 mm across on the scale to create a similar bearing area to that of the plate-shaped specimen. The specimen is compressed between the thumb and forefinger of one hand while simultaneously the same felt pressure is exerted on the scale with the forefinger of the other hand. The scale is read at the failure of the specimen.

For specimens that cannot be broken between thumb and forefinger, the resistance to rupture may be evaluated using a small penetrometer. The specimen is formed by orienting the two larger surfaces parallel to one another and then creating a flat surface. It is placed with one of the larger faces downward on a nonresilient surface. Force is applied through the 6-mm-diameter penetrometer tip until rupture occurs.

Table 3-8

Rupture Resistance Classes Applied to Crushing Plate-Shaped Specimens

Classes	Force *(newtons)*
Fragile	< 3 N
Extremely weak	Not removable
Very weak	Removable; < 1 N
Weak	1 to < 3 N
Medial	3 to < 20 N
Moderate	3 to < 8 N
Moderately strong	8 to < 20 N
Resistive	≥ 20 N
Strong	20 to < 40 N
Very strong	40 to < 80 N
Extremely strong	≥ 80 N

Plasticity

Plasticity is the degree to which puddled soil material is permanently deformed without rupturing by force applied continuously in any direction. Table 3-9 lists the classes and their criteria. Plasticity is determined on material smaller than 2 mm.

The determination is made using thoroughly puddled soil material at a water content where maximum plasticity is expressed. This water content is above the plastic limit but less than the water content at which maximum stickiness is expressed. The water content is adjusted by adding or removing water during hand manipulation. The plastic limit used in engineering classifications, which is closely related, indicates the water content at which a roll that consists of < 0.4 mm material, is 3 mm in diameter, and was formed at a higher water content breaks apart (method D 4318 in ASTM, 2011).

Table 3-9

Plasticity Classes

Classes	Criteria
Nonplastic	A roll 4 cm long and 6 mm thick that can support its own weight if held on end cannot be formed.
Slightly plastic	A roll 4 cm long and 6 mm thick can be formed and can support its own weight if held on end. A roll 4 mm thick cannot support its own weight.
Moderately plastic	A roll 4 cm long and 4 mm thick can be formed and can support its own weight, but a roll 2 mm thick cannot support its own weight.
Very plastic	A roll 4 cm long and 2 mm thick can be formed and can support its own weight.

Toughness

Toughness is related to plasticity. Table 3-10 lists the classes and their criteria. The classes are based on the relative force necessary to form, with the fingers, a roll 3 mm in diameter of < 2 mm soil material at a water content near the plastic limit (test D 2488 in ASTM, 2011).

Table 3-10

Toughness Classes

Classes	Criteria
Low	The specimen diameter at or near the plastic limit can be reduced to 3 mm by exertion of < 8 N.
Medium	The specimen diameter at or near the plastic limit requires 8 to < 20 N to be reduced to 3 mm.
High	The specimen diameter at or near the plastic limit requires > 20 N to be reduced to 3 mm.

Stickiness

Stickiness refers to the capacity of a soil to adhere to other objects. Table 3-11 lists the classes and their criteria. The determination is made on puddled < 2 mm soil material at the water content at which the material is most sticky. The sample is crushed in the hand, water is applied, and manipulation continues between thumb and forefinger until maximum stickiness is reached.

Table 3-11

Stickiness Classes

Classes	Criteria
Nonsticky	After release of pressure, practically no soil material adheres to thumb or forefinger.
Slightly sticky	After release of pressure, soil material adheres perceptibly to both digits. As the digits are separated, the material tends to come off one or the other digit rather cleanly. The material does not stretch appreciably on separation of the digits.
Moderately sticky	After release of pressure, soil material adheres to both digits and tends to stretch slightly rather than to pull completely free from either digit.
Very sticky	After release of pressure, soil material adheres so strongly to both digits that it stretches decidedly when the digits are separated. Soil material remains on both digits.

Manner of Failure

The manner in which specimens fail under increasing force ranges widely and typically is highly dependent on water state. The categories of manner of failure are *brittleness*, *fluidity*, and *smeariness* (see table 3-12). To evaluate brittleness or smeariness, a roughly cubical specimen 25–30 mm on edge is pressed between extended forefinger and thumb. To evaluate fluidity, a handful of soil material is squeezed in the hand (fig. 3-28). Some soil materials are brittle even wet, some can be compressed markedly without cracks appearing, others behave like liquids if wet, and others smear if subjected to shear stress until failure. Soil in the slightly moist or dry states, if coherent, is nearly always brittle and commonly does not exhibit smeariness; consequently, manner of failure is generally only useful for moderately moist or wetter soil material. Smeariness is a property most commonly associated with soils having andic soil properties (i.e., soils classified as Andisols and some Spodosols).

Table 3-12

Manner of Failure Classes

Classes	Operation	Test result
Brittleness		
Brittle	Gradually increasing compressive pressure is applied to a 25–30 mm specimen held between extended thumb and forefinger.	Specimen retains its size and shape (no deformation) until it ruptures abruptly into subunits or fragments.
Semi-deformable	Same as above	Deformation occurs prior to rupture. Cracks develop and specimen ruptures before it is compressed to half its original thickness.
Deformable*	Same as above	Specimen can be compressed to half its original thickness without rupture. Radial cracks may appear and extend inward less than half the radius distance under normal compression.
Fluidity		
Nonfluid	A handful of soil material is squeezed in the hand.	No material flows through the fingers after full compression.
Slightly fluid*	Same as above	After full compression, some material flows through the fingers but most remains in the palm of the hand.
Moderately fluid*	Same as above	After full pressure, most material flows through the fingers; a small residue remains in the palm of the hand.
Very fluid*	Same as above	Under very gentle pressure, most material flows through the fingers like a slightly viscous fluid and very little or no residue remains.

Classes	Operation	Test result
Smeariness		
Non-smeary	Gradually increasing pressure is applied to a 25–30 mm specimen held between extended thumb and forefinger in such a manner that some shear force is exerted on the specimen.	At failure, the specimen does not change suddenly to a fluid, the fingers do not skid, and no smearing occurs.
Weakly smeary	Same as above	At failure, the specimen changes suddenly to fluid, the fingers skid, and the soil smears. Afterward, little or no free water remains on the fingers.
Moderately smeary	Same as above	At failure, the specimen changes suddenly to fluid, the fingers skid, and the soil smears. Afterward, some free water can be seen on the fingers.
Strongly smeary	Same as above	At failure, the specimen changes suddenly to fluid, the fingers skid, and the soil smears and is very slippery. Afterward, free water is easily seen on the fingers.

* The approximate equivalent *n* values (Pons and Zonneveld, 1965) are as follows:

Deformable	< 0.7
Slightly fluid	0.7–1
Moderately fluid	1–2
Very fluid	≥ 2

Penetration Resistance

Penetration resistance is the capacity of the soil in its confined state (*in situ*) to resist penetration by a rigid object. Shape and size of the penetrating object must be defined. Penetration resistance depends strongly on the water state, which should be specified.

Figure 3-28

A field test on a soil with a moderately fluid manner of failure class. (Photo courtesy of John Kelley)

The classes in table 3-13 pertain to the pressure required to push the flat end of a cylindrical rod with a diameter of 6.4 mm a distance of 6.4 mm into the soil in about 1 second (Bradford, 1986). Three generalized classes and seven more narrowly defined classes are used. Orientation of the axis of insertion should be specified. A correction should be made for the weight of the penetrometer if the axis of insertion is vertical and the resistance is small. If rock fragments are present, the lower values measured are typically more descriptive of the fine-earth fabric.

The pocket penetrometer, shown in Bradford (1986), is the standard instrument. Penetrometers with the same 6.4-mm-diameter flat-end tip and a dial reading device are available. The resistance can be read with less variability using the dial device. The scale on the barrel of the pocket penetrometers should be converted to units of force. The supplied scale on such instruments commonly is based on a regression between penetration resistance and unconfined, compressive strength measurements and has no application in the context used here. Penetration resistance is expressed in units of pressure. The preferred unit is the megapascal (MPa). For the 6.4-mm-diameter tip, the measured force in kilograms is

Table 3-13

Penetration Resistance Classes

Classes	Penetration resistance *(MPa)*
Small	< 0.1
Extremely low	< 0.01
Very low	0.01 to < 0.1
Intermediate	0.1 to < 2
Low	0.1 to < 1
Moderate	1 to < 2
Large	> 2
High	2 to < 4
Very high	4 to < 8
Extremely high	> 8

multiplied by 0.31 to obtain the pressure in megapascals. To extend the range of the instrument, weaker and stronger springs may be substituted. Values in megapascals obtained with any diameter of flat-end rod are used to determine the class (see table 3-13).

In addition to the flat-end tip, cone-shaped tips may be mounted on the penetrometers with flat ends as well as other penetrometers. Two 30-degree cone penetrometer tips are specified by the American Society of Agricultural Engineers (Ayers and Perumpral,1982). One has a base area of 1.3 cm^2 and the other of 3.2 cm^2. The tips should be inserted where the base of the cone is flush with the soil surface. Insertion times of 2 seconds and 4 seconds should be used for the smaller and larger cones, respectively. A relationship between the cone tips and the specified rod with a flat end must be established before cone measurements. Table 3-13 can be modified to use the corresponding cone measurements.

Determination of penetration resistance while the soil layer is at or near its maximum water content is useful in evaluation of root limitations. The relationship between penetration resistance and root growth has been the subject of numerous studies—Blanchar et al. (1978), Campbell et al. (1974), Taylor et al. (1966), and Taylor and Ratliff (1969). These studies suggest the following generalities (which can be modified for particular plants and soils): (i) if the soil material is wet or very moist and there are no closely spaced vertical structural planes, the limit of 2 MPa (6.4-mm flat-end rod) indicates strong root restriction for several important annual crops (this is the basis for the penetration resistance criterion in the criteria for physical root restriction); (ii) if MPa is between 2 and 1, root restriction may be assumed to decrease roughly linearly; (iii) if MPa is below 1, root restriction may be assumed to be small.

Excavation Difficulty

Table 3-14 gives the classes of excavation difficulty and their criteria. The classes can be used to describe both non-cemented and cemented or indurated horizons, layers, or pedons for a one-time observation or over time. In most cases, excavation difficulty is related to and controlled by a water state.

Table 3-14

Excavation Difficulty Classes

Classes	Criteria
Low	Material can be excavated with a spade using arm-applied pressure only. Neither application of impact energy nor application of pressure with the foot to a spade is necessary.
Moderate	Arm-applied pressure to a spade is insufficient. Excavation can be accomplished quite easily by application of impact energy with a spade or by foot pressure on a spade.
High	Excavation with a spade can be accomplished, but with difficulty. Excavation is easily possible with a full length pick using an over-the-head swing.
Very high	Excavation with a full length pick using an over-the-head swing is moderately to markedly difficult. Excavation is possible in a reasonable period of time with a backhoe mounted on a 40 to 60 kW (50 to 80 hp) tractor.
Extremely high	Excavation is nearly impossible with a full length pick using an over-the-head arm swing. Excavation cannot be accomplished in a reasonable time period with a backhoe mounted on a 40 to 60 kW (50 to 80 hp) tractor.

Roots

Quantity, size, and location of roots in each layer are recorded. Features of the roots—length, flattening, nodulation, and lesions—and their relationships to special soil attributes or to structure may be recorded as notes.

Quantity of Roots

Quantity of roots is described in terms of numbers of each size per unit area. The observed value is used to assign a class. The classes for quantity of roots pertain to an area in a horizontal plane unless otherwise stated. However, most soil profiles are described from a vertical plane and the number of roots observed per unit area may differ depending on the orientation. Therefore, a horizontal cross-section should be used when practical to determine quantity of roots. The required unit area for observation changes according to root size: 1 cm^2 for very fine and fine roots, 1 dm^2 for medium and coarse roots, and 1 m^2 for very coarse roots.

Ideally, class limits correspond to a root abundance level where there are sufficient roots to exploit much of the soil water that is present in the withdrawal range of the plant over the growing season. This can be difficult because species differ in the efficiency of their roots. Soybeans and cotton are several fold more efficient than grasses, and there are undoubtedly other differences among specific groups. The quantity classes have been formulated so that the *few-common* separation is about where the annual grasses have insufficient numbers of roots for seasonally complete exploitation. The *few* class can be subdivided if useful. The *moderately few-very few* separation is where soybeans and cotton would have insufficient numbers.

The quantity classes are:

Few .... less than 1 per unit area
Very few .... less than 0.2 per unit area
Moderately few ... 0.2 to less than 1 per unit area
Common .... 1 to less than 5 per unit area
Many...................... 5 or more per unit area

Size Classes of Roots

Roots are described in terms of a specified diameter size. The size classes are:

Very fine	less than 1 mm
Fine	1 to less than 2 mm
Medium	2 to less than 5 mm
Coarse	5 less than 10 mm
Very coarse	10 mm or larger

Location of Roots

The location of roots within a layer may be described in relation to other features of the layer. Relationships to layer boundaries, animal traces, pores, and other features are described as appropriate. The description may indicate, for example, whether roots are inside structural units or only along parting planes between structural units. A convenient order is quantity, size, location. The description "many very fine and common fine roots" implies that roots are uniformly distributed, since location is not given. Examples of descriptions with locational information are: "common very fine and common fine roots concentrated along vertical faces of structural units" and "common very fine roots inside peds, many medium roots between structural units."

In some soils, the pattern or root growth may not correspond to soil horizons or layers. A summary statement of root development by increments of 15 cm or 30 cm (or some other convenient thickness) can be helpful. In other soils, root distribution may be summarized by grouping layers. For example, in a soil having a strongly developed clayey illuvial horizon and a horizon sequence of Ap-A-E1-E2-Bt1-Bt2, root development might have one pattern throughout the A horizons, another pattern in the E horizons, and yet another pattern in the B horizons. In this case, root distribution can be described for the A, E, and B horizons, each horizon treated as a whole.

For annual plants, the time of the root observation may be indicated. Root traces (channels left by roots that have died) and the dead roots themselves can be clues to soil properties that change with time. The rate of root decay depends on the species, root size, and the soil moisture and temperature regimes. Local experience can determine the time after maturity or harvest that the root distribution is affected by decay. Root traces in deep layers may persist for years. Many of these traces have organic coatings or linings. If they occur below the normal rooting depth of annual crops, they were left by deeper-rooted plants, perhaps native perennials. The presence of dead roots below the current rooting depth may indicate a change in the soil water regime. The roots may have grown normally for a few years, then died when the soils were saturated for a long period.

In addition to recording the rooting depths at the time of observation, generalizations about the rooting depth may be useful. These generalizations should emphasize very fine and fine roots, if present, because roots of these sizes are active in absorption of water and nutrients. The generalizations may be for a few plants or plant communities that are of particular importance. For observation of annual plants, the generalization should assume plant maturity.

Pores

Pore space is a general term for voids in the soil material. The term includes matrix, non-matrix, and interstructural pore space.

Kinds of Pores

Matrix pores (also called interstitial pores) are formed by the agencies that control the packing of the primary soil particles. In fine and medium textured soils these pores are typically smaller than non-matrix pores. Additionally, their aggregate volume and size change markedly with water state for soil horizons or layers with high extensibility. In coarse textured soils, the interstitial pore size is controlled dominantly by the primary particle packing and remains fairly stable, although pores may become filled with finer material over time.

Non-matrix pores are relatively large voids that occur not only when the soil is dry but also when it is moderately moist or wetter. The voids are not bounded by the planes that delimit structural units. *Interstructural pores* are delimited by structural units. The interstructural porosity may be inferred from the structure description. Commonly, interstructural pores are at least crudely planar.

Non-matrix pores may be formed by roots, animals, compressed air, and other agents. The size distribution of these pores typically is not associated with the particle-size distribution and the related matrix pore-size distribution. For water movement at low suction and conditions of satiation, the non-matrix and interstructural porosity have particular importance.

Non-matrix pores are described by quantity, size, shape, and vertical continuity—generally in that order. Quantity classes pertain to numbers per unit area—1 cm^2 for very fine and fine pores, 1 dm^2 for medium and coarse, and 1 m^2 for very coarse.

Quantity Classes of Pores

The pore quantity classes are:

Few .... less than 1 per unit area
Common .... 1 to less than 5 per unit area
Many.......... 5 or more per unit area

Size Classes of Pores

Pores are described relative to a specified diameter size. The five pore size classes are:

Very fine .... less than 1 mm
Fine........................ 1 to less than 2 mm
Medium .... 2 to less than 5 mm
Coarse.................... 5 to less than 10 mm
Very coarse .... 10 mm or more

Shape Classes of Pores

Common non-matrix pore shapes include:

Vesicular.—Small, approximately spherical or elliptical. These cavities are caused by entrapped air bubbles, most commonly occurring in or below mineral or biological crusts or desert pavement, especially in arid soils. As the size and/or number of near-surface vesicular pores increases, infiltration is drastically reduced and surface runoff increases. A horizon dominated by vesicular pores is identified as a vesicular master horizon (capital letter V).
Tubular.—Approximately cylindrical and elongated, as in worm channels.
Dendritic tubular.—Like tubular, but branching as in root channels.
Irregular.—Nonconnected. These cavities or chambers are commonly called “vughs.”

Continuity Classes of Pores

Vertical continuity involves assessment of the average vertical distance through which the minimum pore diameter exceeds 0.5 mm when the soil layer is moderately moist or wetter. Three classes are used:

Low............ less than 1 cm
Moderate.... 1 to less than 10 cm
High........... 10 cm or more

Additionally, the designation “continuous” is used if the non-matrix pores extend through the thickness of the horizon or layer. Vertical continuity has extreme importance in assessing the capacity of the soil layer to transmit free water vertically.

Special aspects are noted, such as orientation in an unusual direction, concentration in one part of a layer, or conditions where tubular pores are plugged with clay at both ends. Some examples of descriptions of pores are “many fine tubular pores,” “few fine tubular pores and many medium tubular pores with moderate vertical continuity,” and “many medium vesicular pores in a horizontal band about 1 cm wide at the bottom of the horizon.”

Animals

The mixing, changing, and moving of soil material by animals is a major factor affecting properties of some soils. The features resulting from animal activity reflect mainly mixing or transport of material from one part of the soil to another or to the surface. The original material may be substantially modified physically or chemically.

The features that animals produce on the land surface may be described. Termite mounds, ant hills, heaps of excavated earth beside burrows, the openings of burrows, paths, feeding grounds, earthworm castings, other castings, and other traces on the surface are easily observed and described. Simple measurements and estimates (such as the number of structures per unit area, proportionate area occupied, and volume of above-ground structures) give quantitative values that can be used to calculate the extent of activity and even the number of organisms.

The marks of animals below the ground surface are more difficult to observe and measure. Observations are confined mainly to places where pits are dug. The volume of soil generally studied is limiting. For the marks of many animals, the normal pedon for soil characterization is large enough to provide a valid estimate. For some animals, however, the size of the marks is too large for the usual pedon.

Krotovinas are irregular tubular streaks in a layer that consists of material transported from another layer. They are caused by the filling of tunnels made by burrowing animals in one layer with material from outside the layer. In a profile, they appear as rounded or elliptical volumes of various sizes. They may have a light color in dark layers or a dark color in light layers, and their other qualities of texture and structure may be unlike those of the soil around them.

Description of Animal-Related Features

The features produced by animals in the soil are described in terms of amount, location, size, shape, and arrangement and also in terms of the color, texture, composition, and other properties of the component material. There are no special conventions for descriptions. Common words should be used in conjunction with appropriate special terms for the soil properties and morphological features that are described elsewhere in this manual.

Selected Chemical Properties

This section discusses selected chemical properties that are important for describing and identifying soils. Included in the discussion are reaction, carbonates, manganese oxides, salinity, sodicity, sulfates, and sulfides.

Reaction

The numerical designation of reaction is expressed as pH. With this notation, pH 7 is neutral. Values lower than 7 indicate acidity; higher values indicate alkalinity. Soils as a whole range in pH from slightly less than 2.0 to slightly more than 11.0. Individual soils have a much narrower pH range within these overall limits. Reaction varies seasonally and is affected by such factors as moisture, temperature, plant growth, and microbial activity. A significant change in pH also occurs when some naturally wet soils that contain sulfides are drained. In these cases, sulfuric acid forms and pH may decrease to below 2.0.

The standard field pH measurement is performed with a 1:1 soil:water mixture so that comparisons of pH readings are on an equivalent basis. A more dilute sample (for example, a 1:5 soil:water mixture) generally has a higher pH, and less dilute samples generally have lower pH.

While the standard for measuring pH in the field is a 1:1 soil:water mixture, other methods of measuring pH are also used in soil survey for specific purposes, especially those required for some taxonomic criteria in Soil Taxonomy. They include:

0.01 M $CaCl_2$.—This method has the advantage of dampening seasonal variation in pH. It is used for some taxonomic family-level criteria.

1N KCl.—This method is used to infer aluminum saturation levels in some great groups of Oxisols (e.g., Acrudox). If the criteria are met, aluminum toxicity may be a concern.

1M NaF.—This method is used to infer the presence of short-range order minerals. It is used in the criteria for the isotic mineralogy class.

Various methods can be used to measure pH in the field. Pocket pH meters are a popular tool. Care must be taken to clean the sensor tip between readings and to periodically calibrate the meter to standard samples of known pH. It is also important to ensure calibration reagents are fresh. Other common measurement methods include the use of indicator solution dyes, colorimetric kits, and paper pH indicator strips. Proper storage of these materials—out of direct sunlight and not exposed to extreme temperatures—is important. Over time, the test materials become less reliable. It is important to record the method of pH reading.

Reaction Class Terms

Reaction class terms are commonly used to communicate information about soil pH. The terms are given in table 3-15.

Table 3-15

Reaction Class Terms and Their Ranges in pH

Class term	pH range
Ultra acid	< 3.5
Extremely acid	3.5–4.4
Very strongly acid	4.5–5.0
Strongly acid	5.1–5.5
Moderately acid	5.6–6.0
Slightly acid	6.1–6.5
Neutral	6.6–7.3
Slightly alkaline	7.4–7.8
Moderately alkaline	7.9–8.4
Strongly alkaline	8.5–9.0
Very strongly alkaline	> 9.0

Carbonates of Divalent Cations

A solution of cold, 1-normal hydrochloric acid (1N HCl) is used to test for the presence of free carbonates in the field. The proper concentration is made by combining 1 part concentrated HCl (37%) with 11 parts distilled water. Add acid to water, not water to acid. Care must be taken when handling concentrated HCl as it can cause severe skin burns. The application of a few drops of HCl to a sample containing carbonates results in the evolution of CO_2 gas, which forms bubbles (effervescence). The amount and expression of effervescence is affected by size distribution of the carbonates and their mineralogy as well as the overall amount of carbonates present. Consequently, effervescence is a qualitative test and cannot be used to estimate the quantitative amount of carbonate.

Effervescence Class Terms

The five classes of effervescence and their criteria are shown in table 3-16.

Table 3-16

Effervescence Class Terms

Effervescence class	Criteria
Noneffervescent	No bubbles form
Very slightly effervescent	Few bubbles form
Slightly effervescent	Numerous bubbles form
Strongly effervescent	Bubbles form a low foam
Violently effervescent	Bubbles quickly form a thick foam

An example of the use of effervescence class in a description is "strongly effervescent with 1N HCl." While calcium carbonate reliably effervesces when treated with cold dilute hydrochloric acid, effervescence is not always easily observable for some sandy soils. Dolomite reacts to cold dilute acid slightly or not at all and may be overlooked. It can be detected by heating the sample, using more concentrated acid, and grinding the sample. The effervescence of powdered dolomite with cold dilute acid is slow (a few minutes) and frothy.

Calcium Carbonate Equivalent

Calcium carbonate equivalent refers to the amounts of $CaCO_3$ in soil. Other names include soil carbonate, soil inorganic carbon, pedogenic carbonate, caliche, nari, tosca, croute calcaire, kankar, and soil lime (Monger et al., 2015). The most common mineral form is calcite.

A quantitative field test for measuring the soil carbonate uses a simple volume calcimeter (see Soil Survey Staff, 2009, for details). For this procedure, a small sample (commonly 0.33 g) is placed in a syringe. A

10 percent HCl solution is placed in a second syringe which is connected to the first syringe by a rubber tube. The HCl solution is injected into the syringe containing the soil sample and the evolution of CO_2 gas is recorded and adjusted to compensate for temperature and elevation. Soil carbonate is recorded to the nearest whole number.

Manganese Oxides

Hydrogen peroxide (H_2O_2, 3-4% solution, commonly available in pharmacies) can be used to test for the presence of manganese oxides (MnO_2, a kind of redoximorphic concentration). The effervescence classes used for carbonates (table 3-16) are also used for describing the presence of manganese oxides. The effervescence class and reagent are recorded, e.g., "violently effervescent in 3% H_2O_2."

It should be noted that organic matter also reacts to hydrogen peroxide. This reaction is typically slow, while MnO_2 reacts quickly. Hydrogen peroxide is also used for a color change test to detect the presence of reduced monosulfides (e.g., FeS) in subaqueous soils.

Salinity and Sodicity

Accurate determinations of salinity and sodicity in the field require special equipment and are not necessarily part of each pedon investigation. Reasonable estimates of salinity and sodicity can be made if field criteria are correlated to more precise laboratory measurement.

Salinity

The electrical conductivity (EC) of a saturation paste extract is the standard method for measuring salinity and is denoted as ECe. Electrical conductivity is related to the amount of salts that are more soluble than gypsum in the soil. A small amount (up to 2 dS/m) of dissolved gypsum may also contribute to the EC.

The preparation of a saturation paste extract is most commonly performed in the laboratory rather than in the field. Pocket electrical conductivity meters can be used in the field for measuring electrical conductivity of soil:water solutions of various ratios (e.g., 1:1, 1:2, 1:5, etc.). The EC values recorded reflect the concentration of the mixture. Lower readings are associated with higher amounts of water relative to soil. Electrical conductivity measured this way should be denoted with the soil:water ratio (e.g., $EC_{1:1}$, $EC_{1:5}$). There is no universal correction factor to equate these results to the standard saturation paste extract method performed in the laboratory. General correlations between field-measured EC using a soil:water solution and laboratory-measured ECe for the same samples may be possible for soils in a localized geographic area having similar salt chemistry and other properties and similar environmental conditions. Additional samples having only field-measured EC may then be estimated as to their expected ECe values for classification purposes and assignment to salinity classes. Care must be taken to not extend the relationship beyond the area for which it was established.

The 1:5 soil:water mixture (by volume) is commonly used as a field test for measuring EC of subaqueous soil samples. These results are recorded as described above (e.g., $EC_{1:5}$ 10.5 dS/m). The salinity classes shown in table 3-17 are not applicable to these measurements.

The standard international unit of measure for EC is decisiemens per meter (dS/m) corrected to a temperature of 25 °C. (Millimhos per centimeter [mmhos/cm] are equivalent to dS/m, but this notation is not preferred.) Measured electrical conductivity is reported in soil descriptions. Table 3-17 shows the classes of salinity used if the electrical conductivity (ECe) has not been determined but salinity is inferred.

Table 3-17

Salinity Class Terms

Salinity class	Electrical conductivity (ECe) *dS/m (mmhos/cm)*
Nonsaline	< 2
Very slightly saline	2 to < 4
Slightly saline	4 to < 8
Moderately saline	8 to < 16
Strongly saline	≥ 16

Field measurements of electrical conductivity can be made using other methods, such as electromagnetic induction or salinity probes (see chapter 6). Again, these measures are useful for the area where they are made but the observed values are not equivalent to EC measured with a saturation paste extract or with various soil:water ratios.

Sodicity

The sodium adsorption ratio (SAR) is the standard measure of the sodicity of a soil. It is a measure of the equilibrium between sodium ions in the soil solution and the exchangeable sodium ions adsorbed on the soil cation-exchange complex. The sodium adsorption ratio is calculated from the concentrations (in milliequivalents per liter) of sodium, calcium, and magnesium in the saturation extract:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

Formerly, the primary measure of sodicity was the exchangeable sodium percentage, which equals exchangeable sodium (meq/100 g soil) divided by the cation-exchange capacity (meq/100 g soil) times 100. The test for exchangeable sodium percentage, however, has proved unreliable in soils containing soluble sodium silicate minerals or large amounts of sodium chloride.

Sodium is toxic to some crops and affects soil physical properties, mainly saturated hydraulic conductivity. A sodic condition has little effect on hydraulic conductivity in highly saline soils. A soil that is both saline and sodic may, when artificially drained, drain freely at first. After some of the salt has been removed, however, further leaching of salt becomes difficult or impossible. The sodium adsorption ratio (SAR) typically decreases as a soil is leached because the amount of change depends in part on the composition of the water used for leaching.

The following procedure can be used to predict whether the soil will be sodic after leaching. If the initial SAR is greater than 10 and the initial electrical conductivity is more than 20 dS/m, the SAR is determined on a sample after first leaching it with the intended irrigation water. For soils with an electrical conductivity of more than 20 dS/m, the SAR is determined after first leaching the sample with distilled water to an electrical conductivity of about 4 dS/m.

No classes for sodium levels in the soil are provided. Laboratory analysis is required to document the SAR of individual horizons. Soils that have high sodium levels, but are not otherwise saline, commonly have pH of 9.0 or greater. Soils that are both saline and sodic tend to have pH values of less than 8.5. In addition, some sodic soils, especially in slightly depressional areas, may be black at the surface due to dispersion of clay and organic matter and poor drainage. In some sodic soils, natric horizons exhibit columnar structure.

Sulfates

Gypsum (hydrous calcium sulfate: $CaSO_4 \cdot 2H_2O$) can be inherited from the parent material or can precipitate from supersaturated solutions in the soil or substratum. It can alleviate the negative effects of sodium on soil structure, allowing the use of irrigation water that has a relatively high amount of sodium. Soils that contain large amounts of gypsum can settle unevenly after irrigation, and frequent releveling may be required. Soil subsidence due to gypsum dissolution, especially from concentrated flow of rainwater from roofs or paved areas, can be a serious hazard to roads and buildings. Gypsum is soluble in water. The electrical conductivity of a distilled water solution with gypsum is about 2 dS/m. In the absence of other salts, salinity is not a hazard except for such sensitive plants as strawberries and some ornamentals. Gypsum and other sulfates may cause damage to concrete.

Gypsum is commonly tabular or fibrous and tends to accumulate as clusters of crystals or as coats on peds. Some is cemented. Gypsum can typically be identified by its form and lack of effervescence with acid. Gypsum in parent material may not be readily identifiable. If determined, the amount of gypsum is given in the description. If not, the amount may be estimated. Semiquantitative field methods for determining amounts of gypsum are available.

Some soils contain large amounts of sodium sulfate, which looks like gypsum in hand specimens of soil. Sodium sulfate is in the form of thenardite (Na_2SO_4) at temperatures above 32.4 °C and in the form of mirabilite ($Na_2SO_4 \cdot 10H_2O$) at lower temperatures. The increase in volume and decrease in solubility as thenardite changes to mirabilite can cause extreme salt heaving. In saline-sodium soils, sodium sulfate is a common water-soluble salt.

Sulfides

Sulfides, mainly iron sulfide, occur in some tidal marsh soils and in some sedimentary rocks, such as those associated with coal or shale. In marsh soils, soil layers with significant sulfide content are commonly permanently saturated and are neutral in color (N) or have hue of 5Y, 5GY, 5BG, or 5G; value of 2, 3, or 4; and chroma of 1 or less (Fanning et. al., 2002; IUSS Working Group WRB, 2015). When these materials are exposed (e.g., when marsh soils are drained or sulfide-bearing rock is excavated), oxidation commonly produces sulfuric acid. Sulfuric acid is toxic to plants and animals in the soil and to fish and other aquatic organisms in nearby waters. The solutions produced are extremely acid and are highly corrosive to exposed metal and concrete. Soils and rock that may have potential sulfur acidity (especially material dredged from coastal water areas and applied on the land) should be tested for the presence of sulfide salts.

A few soils with appreciable amounts of sulfides contain enough carbonates to neutralize all or part of the acidity when the sulfides are oxidized. In these soils, the total amounts of both calcium carbonate and sulfides are needed to determine if effective neutralization can occur naturally.

No reliable field methods are available for determining the amount of sulfides in marshes. A simple test to confirm the presence of sulfides (but not the amount) uses 30% hydrogen peroxide (H_2O_2) to determine if rapid oxidation causes a significant decrease in pH as compared to a similar sample treated with water (Soil Survey Staff, 2009).

Marsh soils may give off a sulfurous odor. This odor is not a reliable indicator of the presence of significant amounts of oxidizable sulfides; however, odor can be a reliable indicator that sulfides are present. The sulfurous odor ("rotten egg smell"), if detected, should be noted in the soil description. Qualitative class terms for odor intensity are:

Slight.—Odor is faint, only detected close to nose.
Moderate.—Odor is readily noticeable, even at arm's length from the nose.
Strong.—Odor is intense and readily noticed as soon as sample is exposed to the air.

Drained or excavated marsh soils that contain large amounts of sulfides commonly have yellow efflorescences of the mineral jarosite on the exteriors of clods (fig. 3-29).

Two simple laboratory tests are commonly used to detect excess oxidizable sulfides (Soil Survey Staff, 2009). In one test, pH is measured before and after the soil is incubated for several weeks at field capacity. A large drop in pH, or a pH of 3.5 or less after drying, indicates excessive amounts of sulfides. In the other test, the sample is treated with 30- to 36-percent hydrogen peroxide and heated to complete oxidation and to drive off the excess peroxide. Then, pH is measured. If the decrease in pH is large, sulfides are probably present. Use of an electronic meter rather than colorimetric methods to measure pH is preferred because of the possible oxidation of indicator dyes. Special dyes suitable for this test are available. If the qualitative tests for oxidizable sulfides are positive, laboratory determinations of sulfur content are required for precise interpretations and recommendations regarding use and management.

Soil Water

This section discusses "water regimes"—schemes for the description of the state of the soil water at a particular time and for the change in soil water state over time. Soil water state is evaluated from water suction, quantity of water, whether the soil water is liquid or frozen, and the

Figure 3-29

Jarosite concentrations (yellowish color) that formed due to oxidation in this drained marsh soil containing sulfides.

occurrence of free water within the soil and on the land surface. The complexity and detail of water regime statements can range widely.

Inundation Classes

Free water may occur above the soil. Inundation is the condition when the soil area is covered by liquid free water. Flooding is temporary inundation by flowing water. If the water is standing, as in a closed depression, the term ponding is used. Flooding and ponding are temporal conditions. In most cases, soils are not described while inundated (exceptions include subaqueous soils and some soils that are subject to ponding of very long duration). To the extent possible, estimates for inundation should include frequency, duration, and months of occurrence. Depth of inundation is also commonly recorded. Table 3-18 shows the classes for frequency and duration of inundation. The *rare* and *very rare* frequency classes may be combined. The *very frequent* class takes precedence over *frequent* if both definitions are met. *Very frequent* flooding includes tidal inundation. Frequency of flooding should reflect the current conditions. A soil that would be frequently flooded in its natural state, but is now protected by a dam or levee, should be assigned the class that reflects the level of protection provided.

Table 3-18

Frequency and Duration of Inundation Classes (Flooding or Ponding)

Class	Criteria
Frequency	
None	No reasonable possibility of inundation; one chance out of 500 in any year or less than 1 time in 500 years.
Very rare	Inundation is very unlikely but is possible under extremely unusual weather conditions; less than 1 percent chance in any year or less than 1 time in 100 years but more than 1 time in 500 years.
Rare	Inundation is unlikely but is possible under unusual weather conditions; 1 to 5 percent chance in any year or nearly 1 to 5 times in 100 years.
Occasional	Inundation is expected infrequently under usual weather conditions; more than 5 to 50 percent chance in any year or 6 to 50 times in 100 years.
Frequent	Inundation is likely to occur often under usual weather conditions; more than 50 percent chance in any year (i.e., more than 50 times in 100 years) but 50 percent or less chance in all months in any year.
Very frequent	Inundation is likely to occur very often under usual weather conditions; more than a 50 percent chance in all months of any year.
Duration	
Extremely brief	0.1 hour to less than 4 hours (flooding only)
Very brief	4 hours to less than 48 hours
Brief	2 days to less than 7 days
Long	7 days to less than 30 days
Very long	30 or more days

Internal Soil Water State

This section discussions the occurrence of water within the soil, classes used to describe the soil water state at the time the soil is described, and methods for evaluating soil water in the field.

Classes

In describing classes of soil water state for individual layers or horizons, only matrix suction is considered in the definition of the classes.[3] Osmotic potential is not considered. For water contents of medium and fine textured soil materials at suctions of less than about 200 kPa, the reference laboratory water retention is for the natural soil fabric. Class limits are expressed both in terms of suction and water content. To make field and field office evaluation more practicable, water content refers to gravimetric rather than volumetric quantities. The classes apply to mineral and organic soil material. The frozen condition is indicated separately by the symbol "f." This symbol indicates the presence of ice; some of the water may not be frozen. If the soil is frozen, the water content or suction pertains to what it would be if not frozen.

Three classes and eight subclasses for water state are defined in table 3-19. Classes and subclasses may be combined as desired. The desired specificity and characteristics of the water desorption curve determine whether classes or subclasses should be used. Coarse soil material has little water below the 1500 kPa retention, and so subdivisions of dry generally are not useful.

Dry is separated from *moist* at 1500 kPa suction. *Wet* is separated from *moist* at the condition where water films are readily apparent. The water suction at the moist-wet boundary is assumed to be about 0.5 kPa for coarse soil materials and 1 kPa for other materials. The formal definition of coarse soil material is given later.

Three subclasses of dry are defined—*very dry, moderately dry*, and *slightly dry*. Very dry cannot be readily distinguished from air dry in the field. The water content extends from ovendry to 0.35 times the water retention at 1500 kPa. The upper limit is roughly 150 percent of the air-dry water content. The limit between moderately dry and slightly dry is a water content 0.8 times the retention at 1500 kPa.

The **moist** class is subdivided into *slightly moist, moderately moist,* and *very moist*. Depending on the kind of soil material, laboratory retention at 5 or 10 kPa suction (method 4B, Soil Survey Staff, 2014a) determines the *upper water retention* (UWR). A suction of 5 kPa is used for coarse soil material; a suction of 10 kPa is used for other material.

To be considered coarse, the soil material that is strongly influenced by volcanic ejecta must be nonmedial and have few or no vesicular pores in the mineral particles. If not strongly influenced by volcanic ejecta, it must meet the sandy or sandy-skeletal family particle-size criteria and also

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[3] The primary unit for suction is the pascal (Pa). The kilopascal (kPa), equal to 1000 pascals, is commonly employed. One kPa = 1000 Pa = .01 bar = 10 cm of H_2O.

Table 3-19

Water State Classes

Class	Criteria[a]
Dry (D)	> 1500 kPa suction
Very dry (DV)	< 0.35 x 1500 kPa retention
Moderately dry (DM)	0.35 to < 0.8 x 1500 kPa retention
Slightly dry (DS)	0.8 to 1.0 x 1500 kPa retention
Moist (M)	≤ 1500 kPa to > 1.0 or 0.5 kPa[b]
Slightly moist (MS)	1500 kPa suction to MWR[c]
Moderately moist (MM)	MWR to UWR[c]
Very moist (MV)	UWR to > 1.0 or 0.5 kPa[b] suction
Wet (W)	≤ 1.0 kPa or 0.5 kPa[b]
Nonsatiated[d] (WN)	> 0.0 to ≤ 1.0 kPa or ≤ 0.5 kPa[b]
Satiated[e] (WA)	≤ 0.0 kPa

[a] Criteria use both suction and gravimetric water contents as defined by suction.
[b] 0.5 kPa only if coarse soil material (see text).
[c] UWR indicates upper water retention, which is the laboratory water retention at 5 kPa for coarse soil material and 10 kPa for other material (see text). MWR indicates midpoint water retention, which is halfway between the upper water retention and the retention at 1500 kPa.
[d] Peds glisten; no free water present.
[e] Peds glisten; free water present.

be coarser than loamy fine sand, have less than 2 percent organic carbon, and have less than 5 percent water at 1500 kPa suction. Furthermore, the computed total porosity of the < 2 mm fabric must exceed 35 percent.[4]

Very moist has an upper limit at the moist-wet boundary and a lower limit at the upper water retention. Similarly, *moderately moist* has an

[4] Total porosity = 100 - (100 x Db/Dp), where Db is the bulk density of the < 2 mm material at or near field capacity and Dp is the particle density. The particle density may be computed from the following:
Dp = 100/[[(1.7xOC)/Dp1] + [(1.6xFe)/Dp2] + [[100 - [(1/7xOC) + (1.6xFe)]]/Dp3]]
where OC is the organic carbon percentage and Fe is the extractable iron by method 6C2 (Soil Survey Staff, 2014a) or an equivalent method. The particle density of the organic matter (Dp1) is assumed to be 1.4 Mg/m^3, that of the minerals from which the extractable iron originates (Dp2) to be 4.2 Mg/m^3, and that of the material exclusive of the organic matter and the minerals contributing to the extractable Fe (Dp3) to be 2.65 Mg/m^3.

upper limit at the upper water retention and a lower limit at the midpoint in gravimetric water content between retention at 1500 kPa and the upper water retention. This lower limit is referred to as the *midpoint water retention* (MWR). *Slightly moist* extends from the midpoint water retention to the 1500 kPa retention.

The **wet** class has *nonsatiated* and *satiated* subclasses distinguished on the basis of absence or presence of free water. Miller and Bresler (1977) defined satiation as the condition in which free water first appears through saturation. The nonsatiated wet state may be applicable at zero suction to horizons with low or very low saturated hydraulic conductivity. These horizons may not exhibit free water. Horizons may have parts that are *satiated wet* and other parts that are *nonsatiated wet* because of low matrix saturated hydraulic conductivity and the absence of conducting macroscopic pores. Free water develops positive pressure with depth below the top of a wet satiated zone.

A class for saturation (that is, zero air-filled porosity) is not provided because the term suggests that all of the pore space is filled with water. This condition typically cannot be evaluated in the field. Furthermore, if saturation is used for the concept of satiation, then a term is not available to describe known saturation. There is an implication of saturation if the soil material is satiated wet and coarse textured or otherwise has properties indicative of high or very high saturated hydraulic conductivity throughout the mass. A satiated condition does not necessarily indicate reducing conditions. Air may be present in the water and/or the microbiological activity may be low. The presence of reducing conditions may be inferred from soil color in some cases. A test may be performed for ferrous iron in solution. The results of the test for ferrous iron should be reported separately from the water state description.

Evaluation

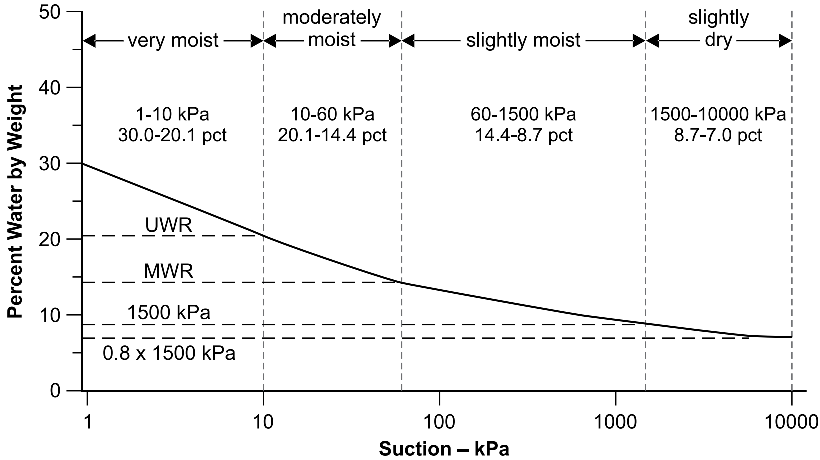
Wet is indicated by the occurrence of prominent water films on surfaces of sand grains and structural units that cause the soil material to glisten. If free water is absent, the term *nonsatiated wet* is used. If free water is present, the term *satiated wet* is used. In the field, the position of the uppermost boundary in the soil profile meeting the satiated wet class is the top of the water in an unlined bore hole after equilibrium has been reached. Lined bore holes or piezometers, installed to several depths across the zone of free water occurrence, are needed to determine the thickness of a perched zone of free water. Piezometers are tubes placed to a designated depth that are open at both ends. They may have a perforated zone at the bottom but do not permit water entry along most of their length. For the purpose of simply obtaining information about the depth of free water and the location and thickness of the free water zone, the installation of bore holes or piezometers is not required. This information can be obtained in the course of observing soils during regular soil survey field operations. Additional information about piezometers can be found in *Installing Monitoring Wells in Soils* (Sprecher, 2008).

Ideally, evaluation within the moist and dry classes should be based on field instrumentation. However, this instrumentation is typically not available and approximations must be made. Gravimetric water content measurements may be used. To make the conversion from measured water content to suction, information is needed on the gravimetric water retention at different suctions. The water retention at 1500 kPa may be estimated from the field clay percentage evaluation if dispersion of clay is relatively complete for the soils concerned. Commonly, the 1500 kPa retention is roughly 0.4 times the clay percentage. This relationship can be refined considerably as the soil material composition and organization are increasingly specified. Another rule of thumb is that the water content at air dryness is about 10 percent of the clay percentage, assuming complete dispersion of clay. Model-based curves that relate gravimetric water content and suction are available for many soils (Baumer, 1986). These curves may be used to determine upper water retention and the midpoint water retention and to place the soil material in a water state class based on gravimetric water contents. Furthermore, in many cases they can be used as the basis for estimating water retention at 10 kPa from measurements at 33 kPa. Figure 3-30 shows a model-based curve for a medium textured horizon and the relationship of water state class limits to water contents determined from the desorption curve. The figure includes the results of a set of tests designed to provide local criteria for field and field office evaluation of water state. These tests are discussed later in this chapter.

Commonly, information on gravimetric water content is not available. Visual and tactile observations must suffice for the placement. Separation between moist and wet and the distinction between the two subclasses of wet may be made visually, based on water-film expression and presence of free water. Similarly, the separation between very dry and moderately dry can be made by visual or tactile comparison of the soil material at the field water content and after air drying. The change on air drying should be very small if the soil material initially is in the very dry class.

Criteria are more difficult to formulate for soil material that is between the moist-wet and the moderately dry-very dry separations. Four tests useful for mineral soils are the color value, ball, rod, and ribbon tests. The three tests that involve tactile examination are performed on soil

Figure 3-30



Model-based curve for a medium textured horizon and the relationship of water state class limits to water contents determined from the desorption curve.

material that has been manipulated and mixed. This manipulation and mixing must be thorough enough to break down aggregates and provide consistent, repeatable results. The change may be particularly large for dense soil. In the field, this limitation should be kept in mind.

Color value test.—The crushed color value of the soil for an unspecified water state is compared to the color value when the soil is at air dryness and when it is moderately moist or very moist. This test generally is useful only if the full range of color value from air dry to moderately moist exceeds one unit of color value. The change in color value and its interpretation depend upon the water desorption characteristics of the soil material. For example, as the water retention at 1500 kPa increases, the difference between the minimum color value in the dry state and the color value in the very moist state tends to decrease.

Ball test.—A quantity of soil is squeezed firmly in the palm of the hand to form a ball about 3 to 4 cm in diameter. This is done in about five squeezes. The sphere should be near the maximum density that can be obtained by squeezing. Different people will prepare the ball differently; however, an individual should learn to perform the procedure consistently.

In one approach, the ball is dropped from progressively increasing heights onto a nonresilient surface. The height in centimeters at which rupture occurs is recorded. Typically heights above 100 cm are not measured. Additionally, the manner of rupture is recorded. If the ball flattens and does not rupture, the term "deforms" is used. If the ball breaks into about five or fewer units, the term "pieces" is used. Finally, if the ball breaks into five or more units, the term "crumbles" is used.

Another approach uses penetration resistance. A penetrometer is inserted in the ball the same way it is done for soil in place. This alternative is only applicable for medium and fine textured soil materials at higher water contents because these materials are relatively plastic and not subject to cracking.

Rod test.—The soil material is rolled between the thumb and forefinger or on a surface to form a rod 3 mm or less in diameter. A rod 2 cm or more in length must be able to remain intact while being held vertically from one end. If the maximum length that can be formed is 2 to 5 cm, the rod is weak. If the maximum length equals or exceeds 5 cm, the rod is strong.

The rod test has close similarities to the plastic limit test (ASTM, 2011). Plastic limit values exceed the 1500 kPa retention at moderate clay contents and approach, but are not commonly lower than, the 1500 kPa retention at high clay contents. If a strong rod can be formed, the water content typically exceeds the 1500 kPa retention. The same is generally true for a weak rod. An adjustment is necessary if 2 to 0.5 mm material is present because the plastic limit is measured on material that passes a number 40 sieve (0.43 mm in diameter).

Ribbon test.—The soil material is smeared out between thumb and forefinger to form a flattened body about 2 mm thick. A ribbon must be at least 2 cm in length. If the maximum length possible is 2 to 4 cm, the ribbon is weak. If the maximum length possible is 4 cm or more, the ribbon is strong.

General relationships of the tests to water state, with the exception of the relationship of the rod test to 1500 kPa retention, have not been formulated. Locally applicable field criteria can be formulated using groupings of soils based on composition.

Natural Drainage Classes

Natural drainage class refers to the frequency and duration of wet periods under conditions similar to those under which the soil developed. Alteration of the water regime by humans, either through drainage or irrigation, is not a consideration unless the alterations have significantly changed the morphology of the soil. Descriptions of these classes follow.

Excessively drained.—Water is removed very rapidly. Internal free water occurrence commonly is very rare or very deep. The soils are commonly coarse textured and have very high saturated hydraulic conductivity or are very shallow.

Somewhat excessively drained.—Water is removed from the soil rapidly. Internal free water occurrence commonly is very rare or very deep. The soils are commonly coarse textured and have high saturated hydraulic conductivity or are very shallow.

Well drained.—Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified. Water is available to plants throughout most of the growing season in humid regions. Wetness does not inhibit root growth for significant periods during most growing seasons. The soils are mainly free of, or are deep or very deep to, redoximorphic features related to wetness.

Moderately well drained.—Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence is commonly moderately deep and transitory through permanent. The soils are wet for only a short time within the rooting depth during the growing season but long enough that most mesophytic crops are affected. They commonly have a moderately low or lower saturated hydraulic conductivity in a layer within the upper 1 meter, periodically receive high rainfall, or both.

Somewhat poorly drained.—Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. Internal free water occurrence is commonly shallow to moderately deep and transitory to permanent. Wetness markedly restricts the growth of mesophytic crops, unless artificial drainage is provided. The soils commonly have one or more of the following characteristics: low or very low saturated hydraulic conductivity, a high water table, additional water from seepage, or nearly continuous rainfall.

Poorly drained.—Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. Internal free water occurrence is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season that most mesophytic crops cannot be grown, unless the soil is artificially drained. The soil, however, is not continuously wet directly below plow depth. Free water at shallow depth is common. The water table is commonly the result of low or very low saturated hydraulic conductivity, nearly continuous rainfall, or a combination of these.

Very poorly drained.—Water is removed from the soil so slowly that free water remains at or very near the surface during much of the growing season. Internal free water occurrence is very shallow and persistent or permanent. Unless the soil is artificially drained, most mesophytic crops cannot be grown. The soils are commonly level or depressed and frequently ponded. In areas where rainfall is high or nearly continuous, slope gradients may be greater.

Subaqueous.—Free water is above the soil surface. Internal free water occurrence is permanent, and there is a positive water potential at the soil surface for more than 21 hours of each day. The soils have a peraquic soil moisture regime.

Internal Free Water Occurrence

Table 3-20 gives the classes and criteria used to describe free water regimes in soils. The term "free water occurrence" is used instead of "satiated wet" in order to facilitate discussion of interpretations. These

Table 3-20

Classes of Internal Free Water

Classes	Criteria
Thickness if perched	
Extremely thin	< 10 cm
Very thin	10 cm to < 30 cm
Thin	30 cm to < 100 cm
Thick	> 100 cm
Depth	
Very shallow	< 25 cm
Shallow	25 cm to < 50 cm
Moderately deep	50 cm to < 100 cm
Deep	100 cm to < 150 cm
Very deep	> 150 cm
Cumulative annual pattern	
Absent	Not observed
Very transitory	Present < 1 month
Common	Present 1 to 3 months
Transitory	Present 4 to 6 months
Persistent	Present 7 to 12 months
Permanent	Present continuously

classes indicate thickness if water is perched, depth to the upper boundary, and the aggregate time of occurrence in the calendar year. The free water need only occur in some parts of the horizon or layer to be recognized. If not designated as perched, the zone of free water is assumed to occur in all horizons or layers from its upper boundary to below a depth of 2 meters or to the depth of observation. Artesian effects also may be noted.

Water State Annual Pattern

The water state annual pattern is a description of field soil water over the year as applied to horizons and layers or to standard depth zones. Table 3-21 gives an example using the classes of internal water states. Months when the layer is frozen are indicated by the symbol "F." Typically, the use of the soil is indicated and the time interval is at least monthly. More general records may be constructed based on less-specific soil uses and on soil concepts at a higher categorical level. Records may be constructed for classes of relative precipitation: *wet*—the wettest 2 years in 10; *dry*—the driest 2 years in 10; and *average*—the conditions 6 years in 10. Unless otherwise indicated, the class placement for relative precipitation is based on the more critical part of the growing season for the vegetation specified in the use. The frequency and duration of inundation for each month also can be given.

Table 3-21

Example of a Water State Annual Pattern

[Months when the layer is frozen are indicated by an "F." Other symbols are defined in table 3-19.]

Depth cm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average 6 years in 10												
Fine, smectitic, mesic Typic Argiudoll [a]												
0–25	MM	MM	MM	MM	MM	MM	MS	DS	DS	MS	MM	MM
	F	F										F
25–50	MM	MM	MM	MM	MM	MM	MM	MS	MS	MS	MS	MM
	F	F	F									
50–100	MS	MS	MM	MM	MM	MM	MM	MS	MS	MS	MS	MS
100–150	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
150–200	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM

Depth cm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fine-loamy, mixed, superactive, thermic Typic Haploxeralf [b]												
0–30	MM	MM	MS	MS	DS	DS	D1[c]	D1	D1	D1	D1	MS
30–70	MM	MM	MM	MM	MS	DS	D1	D1	D1	DS	MS	MM
70–100	MV	MV	MM	MM	MM	MM	MS	D1	D1	D1	D1	MS
120–170	MM	MM	MM	MS	MS	MS	MS	D1	D1	D1	DS	MS
Driest 2 years in 10												
Fine, smectitic, mesic Typic Argiudoll [a]												
0–25	MM	MM	MM	MM	MM	MS	DS	DS	DS	MS	MS	MM
	F	F										F
25–50	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS
	F	F	F									
50–100	MS	MS	MS	MM	MM	MS	MS	MS	MS	MS	MS	MS
100–150	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
150–200	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
Fine-loamy, mixed, superactive, thermic Typic Haploxeralf [b]												
0–30	MS	MM	MS	MS	DS	DS	D1	D1	D1	D1	D1	DS
30–70	MM	MM	MM	MM	MS	DS	D1	D1	D1	D1	MS	MS
70–100	MS	MM	MM	MM	MM	MM	MS	D1	D1	D1	D1	DS
120–170	MS	MM	MS	MS	MS	MS	MS	D1	D1	D1	D1	D1
Wettest 2 years in 10												
Fine, smectitic, mesic Typic Argiudoll [a]												
0–25	MM	MM	MV	MV	MV	MM	MM	MM	MM	MM	MM	MM
	F	F										F
25–50	MM	MM	MV	MV	MM	MM	MM	MM	MM	MM	MM	MM
	F	F	F									
50–100	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
100–150	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
150–200	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM	MM
Fine-loamy, mixed, superactive, thermic Typic Haploxeralf [b]												
0-30	MM	MM	MM	MS	DS	DS	D1	D1	D1	DS	MS	MM
30-70	MV	MV	MM	MM	MS	DS	D1	D1	D1	DS	MM	MV
70-100	MV	MV	MM	MM	MM	MM	MS	D1	D1	D1	MS	MM
120-170	MM	MM	MS	MS	MS	MS	MS	D1	D1	D1	DS	MS

[a] Otoe County, Nebraska (USDA-NRCS, 2009). Aksarben silty clay loam, 2 to 6 percent slopes. Corn (*Zea mays*) following corn. Assume: contoured, terraced, over 20 percent residue cover. Disk twice in April. Field cultivate once. Plant May 1–15. Cultivate once or twice. Harvest November 1–15. Cattle graze after harvest. Based on a discussion with H.E. Sautter, soil scientist (retired), Syracuse, NE. Monthly water states based on long-term field mapping experience and water balance computations.

[b] San Diego Area, California (USDA-SCS, 1973). Fallbrook sandy loam, 5 to 9 percent slopes, eroded. Mean annual precipitation at Escondido is 344 mm, and potential evaporation at Thornwaite is 840 mm. Study area has slightly greater slope than the upper limit of the map unit. Vegetation is annual range, fair condition. Generalizations were made originally for the 1983 National Soil Survey Conference based on field measurements in 1966 by Nettleton et al. (1969), as interpreted by R.A. Dierking, soil correlator, Portland, OR. At the time, moderately dry and very dry were not distinguished.

[c] D1 = very dry and moderately dry water states.

Water Movement

Water movement concerns rates of flow into and within the soil and the related amount of water that runs off and does not enter the soil. Saturated hydraulic conductivity, infiltration rate, and surface runoff are part of the evaluation (see chapter 2 for a discussion about runoff).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. It can be thought of as the ease with which pores of a saturated soil permit water movement. Water movement in soil is controlled by two factors: 1) the resistance of the soil matrix to water flow, and 2) the forces acting on each element or unit of soil water. Darcy's law, the fundamental equation describing water movement in soil, relates the flow rate to these two factors. Mathematically, the general statement of Darcy's law for vertical, saturated flow is:

$$Q/At = -K_{sat}\, dH/dz$$

The flow rate *Q/At* is what soil physicists call the flux density, i.e., the quantity of water *Q* moving past an area *A*, perpendicular to the direction of flow, in a time *t*. The vertical saturated hydraulic conductivity K_{sat} is the reciprocal, or inverse, of the resistance of the soil matrix to water flow. The hydraulic gradient *dH/dz* is the driving force causing water to move in soil, the net result of all forces acting on the soil water. Rate of water movement is the product of the hydraulic conductivity and the hydraulic gradient.

A distinction is made between saturated and unsaturated hydraulic conductivity. Saturated flow occurs when the soil water pressure is positive, i.e., when the soil matric potential is zero (satiated wet condition). In most soils this condition occurs when about 95 percent of the total pore space is filled with water. The remaining 5 percent is filled with entrapped air. If the soil remains saturated for several months or longer, the percent of the total pore space filled with water may approach 100. Saturated hydraulic conductivity cannot be used to describe water movement under unsaturated conditions.

The vertical saturated hydraulic conductivity K_{sat} is the proportionality constant relating soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement in soil. K_{sat} is the reciprocal of the resistance of soil to water movement. As resistance increases, hydraulic conductivity decreases. Resistance to water movement in saturated soil is primarily a function of the arrangement and size distribution of pores. Large, continuous pores have a lower resistance to flow (and thus higher conductivity) than small or discontinuous pores. Soils with high clay content generally have lower hydraulic conductivities than sandy soils because the pore size distribution in sandy soil favors large pores, even though sandy soils typically have higher bulk densities and lower total porosities (total pore space) than clayey soils. As illustrated by Poiseuille's law, the resistance to flow in a tube varies as the square of the radius. Thus, as a soil pore or channel doubles in size, its resistance to flow is reduced by a factor of 4, i.e., hydraulic conductivity increases fourfold.

Saturated hydraulic conductivity can be expressed by different forms of mathematical equations. When the flux and gradient are expressed on a mass basis, the resulting dimensions for K_{sat} are (mass x time)/volume and the SI units (International System of Units) are kg s m^{-3} (kilogram seconds per cubic meter). When they are expressed on a volume basis, the dimensions are (volume x time)/mass and the SI units are m^3 s kg^{-1} (cubic meter seconds per kilogram). If one expresses the flux on a volume basis and the gradient on a weight basis, then the dimensions of K_{sat} are length/time and the SI units are m s^{-1} (meters per second). This last mathematical form has the simplest units, but it only applies under unique conditions in the field. Care must be taken to interpret this correctly and not conclude that hydraulic conductivity is literally the rate of water movement through the soil. Saturated hydraulic conductivity is not a rate of water movement; it is a measure of a saturated soil's ability to transmit water under a hydraulic gradient. Or, in general terms, it is the ease with which pores of a saturated soil permit water to move. Low values indicate restricted movement, and higher values indicate relative ease of movement.

Data on saturated hydraulic conductivity are valuable in overall planning for irrigation, drainage, erosion control, and flood control. K_{sat} can be used to predict flow rate under specified hydraulic gradients and boundary conditions. It is an important component in solute transfer and drainage models. Surface ponding and runoff are regulated to a great extent by saturated hydraulic conductivity. K_{sat} can also be used for estimating transport coefficients of nonaqueous fluids (e.g., air and organic liquids). In addition, because saturated hydraulic conductivity is a powerful indicator of pore geometry, it can be used as an index for soil structure.

Saturated hydraulic conductivity is one of the most variable soil properties. This variability is determined by total porosity, pore-size distribution, and tortuosity of flow paths, all of which are highly affected by land use and management. Different crop management systems on the same soil type may cause 100-fold differences in K_{sat} of surface horizons.

Coefficients of variability in excess of 100 percent for saturated hydraulic conductivity are common. Measured K_{sat} values may vary dramatically with the method used for measurement. Laboratory-determined values rarely agree with field measurements; the differences can be on the order of 100-fold or more. Field methods generally are considered more reliable than laboratory methods, but this may be an illusion due to differences in sample volumes and method. The volume of the sample being tested relates to the possibility of a sample including unusually large pores due to animal burrows, root channels, desiccation cracks, etc. For smaller volumes, this has the character of a "hit or miss" proposition, and the result can be high variability within relatively small areas. For larger sampling volumes, the chance of observing similar K_{sat} values from multiple readings within a study area is higher and the variability among samples is lower. The smallest volume in which the lowest variability can be attained is called the "representative elementary volume" (REV) (Bear, 1972). The REV for K_{sat} measurements is currently unknown. It likely varies by soil type. Because the field is the best setting for approximating a representative elementary volume, field measurements are emphasized.

Because of the highly variable nature of soil hydraulic conductivity, a single measured value is an unreliable indicator of the hydraulic conductivity of a soil. An average of several values provides a reliable estimate, which can be used to place the soil in a particular saturated hydraulic conductivity class. Log averages (geometric means)[5] should be

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[5] $\text{meanKs} = (Ks_1 x Ks_2 x Ks_3 x ... x Ks_x)^{1/x}$

used rather than arithmetic averages because hydraulic conductivity is a property with log-normal distribution. The antilog of the average of the logarithms of individual conductivity values is the log average, or geometric mean, and should be used to place a soil into the appropriate hydraulic conductivity class. Log averages are lower than arithmetic averages.

Classes of saturated hydraulic conductivity.—In this manual, saturated hydraulic conductivity classes are defined in terms of vertical, saturated hydraulic conductivity. Table 3-22 identifies the vertical, saturated hydraulic conductivity classes used in the National Cooperative Soil Survey. The saturated hydraulic conductivity classes in this manual have a wider range of values than the classes that were previously used by the NCSS, as published in the previous edition of the *Soil Survey Manual* (Soil Survey Staff, 1951) and the *Guide for Interpreting Engineering Uses of Soils* (USDA-SCS, 1971). The dimensions of hydraulic conductivity vary depending on whether the hydraulic gradient and flux density have mass, weight, or volume bases. Values can be converted from one basis to another with the appropriate conversion factor. Typically, the hydraulic gradient is given on a weight basis, the flux density is given on a volume basis, and the dimensions of K_{sat} are length per time. The correct SI units are therefore meters per second.[6] Micrometers per second are also acceptable SI units and, due to fewer decimal places, are more convenient (table 3-22). Table 3-23 gives the equivalent class limits in other commonly used units. Converting to equivalent units is useful when presenting the data to members of the public who may not be familiar with SI units.

Table 3-22

Classes of Saturated Hydraulic Conductivity

Class	K_{sat} (μm/s)
Very high	≥ 100
High	10 to < 100
Moderately high	1 to < 10
Moderately low	0.1 to < 1
Low	0.01 to < 0.1
Very low	< 0.01

[6] The Soil Science Society of America prefers that all quantities be expressed on a mass basis. This results in K_{sat} units of kg s m^{-3}. Other acceptable units are m^3 s kg^{-1}, where all quantities are expressed on a volume basis, and m s^{-1}, where hydraulic gradient is expressed on a weight basis and flux density on a volume basis.

Saturated hydraulic conductivity does not describe the capacity of soils in their natural setting to dispose of water internally. A soil placed in a very high class may contain free water because there are restricting layers below the soil or because the soil is in a depression where water from surrounding areas accumulates faster than it can pass through the soil. The water may actually move very slowly despite a high K_{sat}.

Table 3-23

Saturated Hydraulic Conductivity Class Limits in Equivalent Units

µm/s	m/s	cm/day	in/hr	cm/hr	kg s m^{-3}	m^3 s kg^{-3}
100	10^{-4}	864	14.17	36.0	1.02×10^{-2}	1.02×10^{-8}
10	10^{-5}	86.4	1.417	3.60	1.02×10^{-3}	1.02×10^{-9}
1	10^{-6}	8.64	0.1417	0.360	1.02×10^{-4}	1.02×10^{-10}
0.1	10^{-7}	0.864	0.01417	0.0360	1.02×10^{-5}	1.02×10^{-11}
0.01	10^{-8}	0.0864	0.001417	0.00360	1.02×10^{-6}	1.02×10^{-12}

Guidelines for K_{sat} class placement.—Measured values of K_{sat} are available from the literature or from researchers working on the same or similar soils. If measured values are available, their geometric means should be used for class placement.

Saturated hydraulic conductivity is a fairly easy, inexpensive, and straightforward measurement. If measured values are unavailable, a project to make measurements should be considered. Field methods are the most reliable. Standard methods for measurement of K_{sat} are described in Agronomy Monograph No. 9 (Klute and Dirksen, 1986; Amoozegar and Warrick, 1986) and in SSIR 38 (Bouma et al., 1982).

Researchers have attempted to estimate K_{sat} based on various soil properties. These estimation methods typically use one or more of the following soil physical properties: surface area, texture, structure, bulk density, and micromorphology. The success of the individual methods varies, and no single method works well for all soils. In some cases, a method works well only in a localized area. In other cases, measurement of the predictor variables is more difficult than measurement of hydraulic conductivity. Generally, adjustments must be made for soil properties that affect the integrity and continuity of macropores when the soil is moderately moist or wet. These properties include high sodium concentrations; certain clay mineralogies; grade, size, and shape of soil structure; and the presence of coarse fragments, fragipans, cemented layers, and other miscellaneous features.

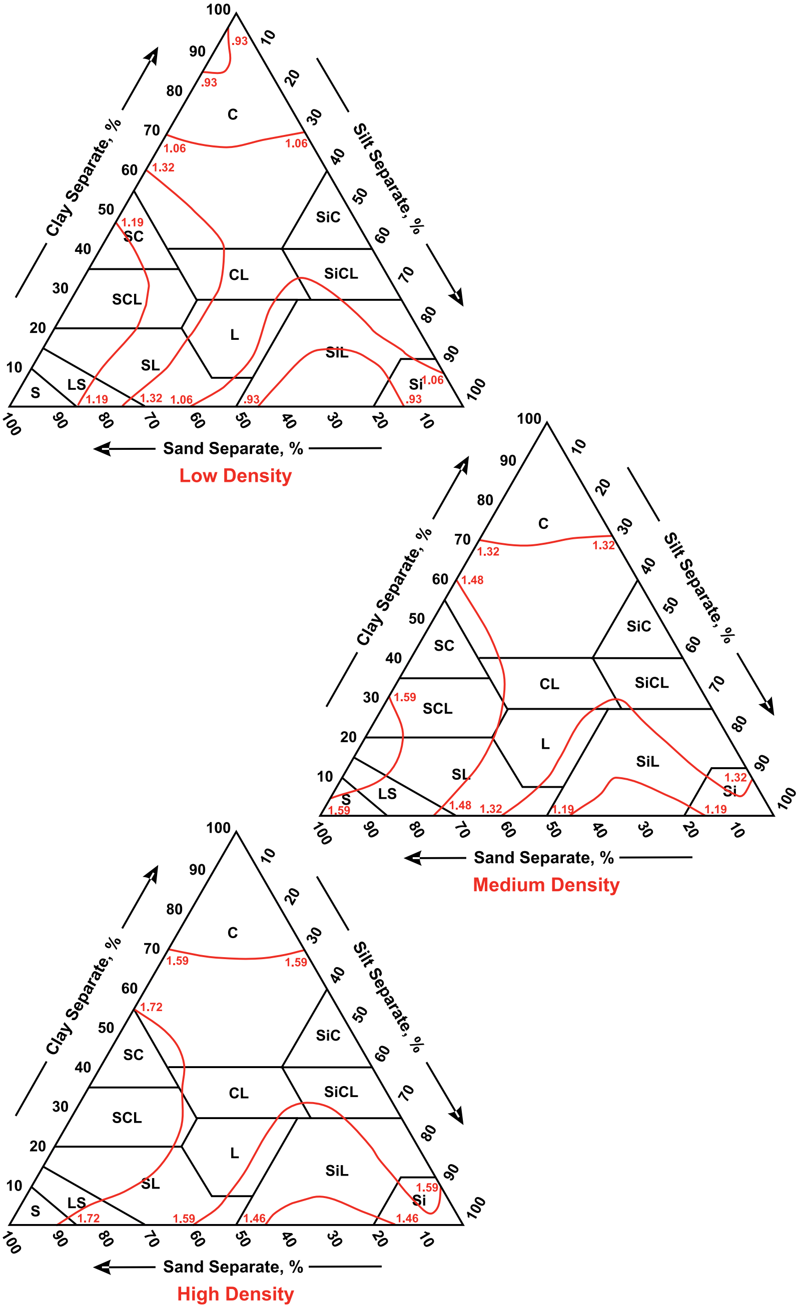
The method presented here is very general (Rawls and Brakensiek, 1983). It was developed from a statistical analysis of several thousand measurements on a variety of soils. It is intended for a wide application and must be used locally with caution. This method does not account for the circumstances mentioned in the previous paragraph. Commonly, the results must be adjusted based on experience and local conditions.

Figures 3-31 and 3-32 used together provide a method for approximating K_{sat} class based on soil texture and bulk density. Each figure consists of three textural triangles. Based on the texture and bulk density of a particular soil horizon, the bulk density class is estimated by determining which triangle in figure 3-31 the horizon belongs to. The chosen bulk density class determines which triangle in figure 3-32 is used to estimate K_{sat} class.

For a particular soil texture with either measured or estimated bulk density, interpolating between the iso-bulk density lines in figure 3-31 yields a bulk density class. The triangle in the figure that provides the value closest to the measured or estimated bulk density for that particular textural class determines which triangle in figure 3-32 should be used. For example, in figure 3-31, a clay loam with both 35 percent sand and clay and a bulk density of 1.20 g/cc plots between the iso-bulk density lines of 1.06 and 1.32 of the textural triangle marked "low" and thus is in the low bulk density class. A clay loam with both 35 percent sand and clay and a bulk density of 1.40 g/cc plots between the iso-bulk density lines of 1.32 and 1.48 on the textural triangle marked "medium" and thus has a medium bulk density class. For soils having medium or average bulk densities, the center triangle is used. The triangles above and below the center triangle are for soils with high and low bulk densities, respectively. The textural triangle in figure 3-32 that corresponds with the bulk density class determined from figure 3-31 is selected, and the clay and sand percentages are plotted to determine K_{sat} class placement. The K_{sat} class is "moderately high" for the clay loam in the low bulk density class and "moderately low" for the clay loam in the medium bulk density class. A numerical value of K_{sat} can be estimated by interpolating between the iso-K_{sat} lines. However, the values should be used with caution. They should be used only to compare classes of soils and not as an indication of the K_{sat} of a particular site. If site values are needed, it is best to make several measurements at the site.

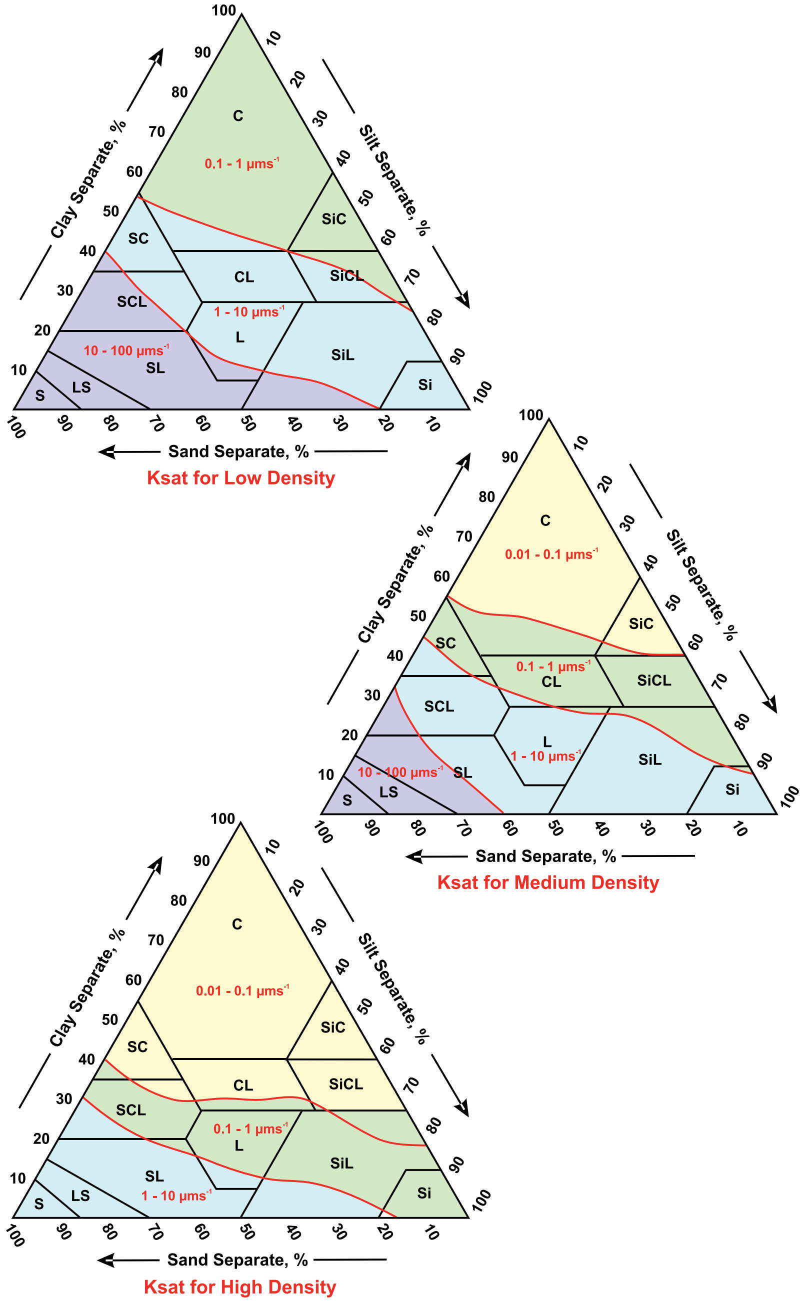
The K_{sat} values determined using the above procedure may need to be adjusted based on other known soil properties. Currently, there are no guidelines for adjusting the estimated K_{sat}. The soil scientist must use best judgment based on experience and the observed behavior of the particular soil.

Figure 3-31



Bulk density classes: low, medium, and high (Rawls and Brakensiek, 1983).

Figure 3-32



Saturated hydraulic conductivity classes based on bulk density and texture relationships.

Saturated hydraulic conductivity can be given for the soil as a whole, for a particular horizon, or for a combination of horizons. The horizon with the lowest value determines the saturated hydraulic conductivity class assigned to the whole soil. If an appreciable thickness of soil above or below the horizon with the lowest value has significantly higher conductivity, then estimates for both parts are typically given (i.e., high over very low).

Infiltration

Infiltration is the process of downward water entry into the soil. It is typically sensitive to near surface conditions as well as to the antecedent water state. Hence, it is subject to significant change with soil use and management and over time. As a result, assigning infiltration values to soil map units for most soil survey projects (unless they are large scale, high-intensity surveys) is generally not practical. The following discussion describing infiltration is provided for background information. Infiltration rate classes are not provided. Field measured values can be recorded as part of the site description for pedons.

Infiltration stages.—Three stages of infiltration may be recognized: preponded (before ponding occurs), transient ponded (ponding is transient), and steady ponded (a constant ponded condition). *Preponded infiltration* pertains to downward entry of water into the soil under conditions where free water is not present on the land surface. At this stage, the rate of water addition determines the rate of water entry. If rainfall intensity increases twofold, then the infiltration increases twofold. In addition, surface-connected macropores are not involved in transporting water downward (water is only moving through the matrix). No runoff occurs during the preponded stage.

As water addition continues, the point may be reached where free water occurs on the ground surface. This condition is called ponding. The term in this context is less restrictive than its use in inundation. The free water may be restricted to depressions and be absent from the majority of the ground surface. Once ponding has taken place, the infiltration is controlled by soil characteristics rather than by the rate of water addition. As a result, surface-connected macropores and subsurface-initiated cracks are involved in transporting water downward.

Infiltration under conditions where free water is present on the ground surface is referred to as ponded infiltration. In the initial stage of ponded infiltration, the rate of water entry typically decreases appreciably with time because of the deeper wetting of the soil, which results in a reduced suction gradient and the closing of cracks and other surface-connected macropores. *Transient ponded infiltration* is the stage at which the ponded infiltration decreases markedly with time. After long, continued wetting under ponded conditions, the rate of infiltration becomes steady. This stage is referred to as *steady ponded infiltration*. Surface-connected cracks, if reversible, close. The suction gradient is small, and the driving force is reduced to near that of the gravitational gradient. If there is no ice and no zones of free water within moderate depths and if surface or near surface features (e.g., a crust) do not control infiltration, the minimum saturated hydraulic conductivity within a depth of ½ to 1 meter is a useful predictor of steady ponded infiltration rate.

Minimum annual steady ponded infiltration.—The steady ponded infiltration rate when the soil is in the wettest state that regularly occurs while not frozen is called the *minimum annual steady ponded infiltration rate*. It can be estimated using the equation for the Green-Ampt infiltration model (see below). The estimated rate is subject to reduction if free water is present at shallow depths. The minimum annual steady ponded infiltration rate has application for prediction of runoff at the wettest times of the year when the runoff potential is typically highest.

Green-Ampt infiltration model.—The Green-Ampt model is one model used to compute infiltration rate. The model assumes that infiltrating water uniformly wets to a depth and stops abruptly at a front. This front moves downward as infiltration proceeds. The soil above the wetting front is in the satiated wet condition throughout the wetted zone.

The equation (Rawls and Brackensick, 1983) describing infiltration is:

$$f = Ka\left(1 + \frac{MxS}{F}\right)$$

Ka is the hydraulic conductivity for satiated, but not necessarily saturated, conditions; *M* is the porosity at a particular water state that has the potential to be filled with water; *S* is the effective suction at the wetting front; and *F* is the cumulative infiltration. The hydraulic conductivity at satiation is somewhat lower than the saturated value because of the presence of entrapped air. The available porosity (M) changes for surficial horizons according to bulk density and for all horizons according to the water state. It is, therefore, sensitive to soil use that may affect both bulk density of surficial horizons and the antecedent water state. The value of the effective suction at the wetting front (S) is determined largely by texture and is a tabulated quantity. The cumulative infiltration (F) increases with time as infiltration proceeds. A consequence of the increase in the cumulative infiltration is that the infiltration rate (f) decreases with time. As the cumulative infiltration becomes large and the depth of wetting considerable, the infiltration rate approaches the value of the hydraulic conductivity for the satiated condition.

Soil Temperature

Soil temperature, like soil moisture, is an important component of the overall soil climate. It exerts a strong influence on biological activities. It also influences the rates of chemical and physical processes within the soil. As a result, the chemical properties of the soil, including organic matter content, mineralogy, and fertility levels, are significantly impacted by soil temperature. When the soil is frozen, biological activities and chemical processes essentially stop. Physical processes that are associated with ice formation are active if unfrozen zones are associated with freezing zones. Below a soil temperature of about 5 °C (referred to as "biologic zero" in *Soil Taxonomy*), growth of roots of most plants is negligible. However, in areas where soils have permanently frozen layers near the surface, even large roots of adapted plants are present immediately above the frozen layer in late summer. Most plants grow best within a restricted range of soil and air temperatures. Knowledge of soil and air temperatures is essential in understanding soil-plant relationships. Temperature, like the soil water state, changes with time. It generally differs from layer to layer at any given time.

Characteristics of Soil Temperature

Heat is both absorbed at and lost from the surface of the soil. Temperature at the surface can change in daily cycles. The soil transmits heat downward when the temperature near the surface is higher than the temperature below. It transmits heat upward when the temperature is warmer within the soil than at the surface. Soil temperatures at various depths within the soil follow cycles. The cycles deeper in the soil lag behind those near the surface. The daily cycles decrease in amplitude as depth increases and are scarcely measurable below 50 cm in most soils. Seasonal cycles are evident to much greater depths if seasonal air temperature differences are pronounced. The temperature at a depth of 10 m is nearly constant in most soils and is about the same as the mean annual temperature of the soil above.

Soil temperature varies at a given site from layer to layer according to the time of the year; yet, if the average annual temperatures at different depths in the same pedon are compared, they typically do not differ. Mean annual soil temperature is one of several useful values that describe the temperature regime of a soil.

The seasonal fluctuation of soil temperature is a characteristic of a soil. Soil temperature fluctuates little seasonally near the equator; it fluctuates widely according to season in the middle and high latitudes. Mean seasonal temperatures can be used to characterize soil temperature. As soil depth increases, the magnitude of the differences in seasonal soil temperature decreases and the seasonal cycles exhibit a delay compared to temperatures at shallower depths.

For soils that freeze in winter, soil temperature is influenced by the release of heat when water changes from liquid to solid. This release is about 80 calories per gram of water. Heat must be dissipated before the water in soil freezes. The rate of thaw of frozen soils is slower, because heat is required to warm the soil in order to melt the ice. In areas of heavy snowfall, the snow provides an insulating blanket and soils do not freeze as deeply or do not freeze at all.

Many factors influence soil temperature. They include amount, intensity, and distribution of precipitation; daily and monthly fluctuations in air temperature; insolation; kinds, amounts, and persistence of vegetation; duration of moisture states and snow cover; kinds of organic deposits; surface soil color; aspect and gradient of slope; elevation; and ground water. All of these factors may be described in a soil survey.

Estimating Soil Temperature

Soil temperature can be monitored over time through the use of automated digital temperature recorders. The recorders are commonly buried in water-tight containers in the soil. They automatically record and store temperature readings at preprogrammed intervals throughout the day (five readings per day is sufficient). Sensors at the ends of wire leads extending from the buried container are commonly placed about 1 meter above the ground (for air temperature) and at a depth of 50 cm in the soil. Additional sensors can be placed at other depths if desired. At the end of the study period (generally 1 year), the recording device is retrieved and the data are downloaded to a computer for analysis. From these data one can calculate mean annual soil temperature as well as mean annual summer and winter temperatures. The relationship between average soil temperature and average air temperature can also be determined for the site. Plots of diurnal, seasonal, and annual temperature variation can be prepared to illustrate the variation of soil temperature through time.

Estimates of soil temperature can be made without 1 or more complete years of collected data. Mean annual soil temperature in temperate, humid, continental climates can be approximated by adding 1 °C to the mean annual air temperature reported by standard meteorological stations at locations near the soil under study. The mean annual soil temperature at a given place can be estimated more reliably by a single reading at a depth of 10 m. If water in wells is at depths between 10 and 20 m, the temperature of the water typically gives a close estimate of mean annual soil temperature. Mean annual soil temperature can also be estimated from the average of four readings at about 50 cm or greater depth, equally spaced throughout the year.

The mean soil temperature for summer can be estimated by averaging three measurements taken at a constant depth between 50 cm and 1 m on the 15th day of each of the three months of the season. Similar methods may be used to estimate soil temperature for other seasons. These methods give values slightly different from the actual soil temperature, due to factors such as vegetation (particularly density of canopy), ground water, snow, aspect, rain, unusual weather conditions, and other factors. Tests for nearly level, freely drained soils, both grass-covered and cultivated, produce comparable values. Over the usual period of a soil survey, systematic studies can be made to establish temperature relationships in the survey area.

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CHAPTER 4

Soil Mapping Concepts

By Soil Science Division Staff. Revised by Kenneth Scheffe and Shawn McVey, USDA-NRCS.

Soil Mapping Process

Soil mapping is the process of delineating natural bodies of soils, classifying and grouping the delineated soils into map units, and capturing soil property information for interpreting and depicting soil spatial distribution on a map.

The soils and miscellaneous areas (e.g., Rock outcrop) in a survey area are in an orderly pattern that is related to the geology, landforms, topography, climate, and natural vegetation. Each kind of soil and miscellaneous area is associated with a particular kind of landform or with a segment of the landform. Soil scientists delineate these repeating patterns of landform segments, or natural bodies, on a map. By observing the soils and miscellaneous areas in the survey area and relating their position to specific segments of the landform, a soil scientist develops a concept, or model, of how they formed. Thus, during mapping, these models enable the soil scientist to predict with considerable accuracy the kind of soil or miscellaneous area on the landscape (Hudson, 1992).

The repetitive patterns imprinted in soils by the soil-forming factors can be observed at scales ranging from continental to microscopic. These patterns are the basis for soil identification and mapping at different scales. A system of terminology, definitions, and operations can be ascribed to the various scales. Hierarchical systems of classes and subclasses are established to produce groupings at the different scales.

Commonly, individual soils on the landscape merge into one another as their characteristics gradually change. To construct an accurate soil map, however, soil scientists must determine the boundaries between the soils. Some boundaries are sharp, where soils change over a few meters, while others are more gradual. Soil scientists can observe only a limited number of pedons. Nevertheless, these observations, supplemented by an understanding of the soil-vegetation-landscape relationship, are sufficient to verify predictions of the kinds of soil and to determine their boundaries.

Soil scientists record the characteristics of the pedons, associated plant communities, geology, landforms, and other features that they study. They describe the kind and arrangement of soil horizons and their color, texture, size and shape of soil aggregates, kind and amount of rock fragments, distribution of plant roots, reaction, and other features that enable them to classify and identify soils (see chapters 2 and 3 for details). They describe plant species present (their combinations, productivity, and condition) to classify plant communities, correlate them to the soils with which they are typically associated, and predict their response to management and change. After the soil scientists identify and describe the properties of landscape components, or natural bodies of soils, the components are correlated to an appropriate taxonomic class, which is used for naming map units. Correlation, or comparison of individual soils with similar soils in the same taxonomic class in other areas, confirms data and helps the staff determine the need to assemble additional data. Taxonomic classes are concepts. Each taxonomic class has a set of soil characteristics with precisely defined limits. The classes are used as a basis for comparison to classify soils systematically. Soil Taxonomy, the system of taxonomic classification used in the United States, is based mainly on the kind and character of soil properties and the arrangement of horizons within the profile (Soil Survey Staff, 1999).

While a soil survey is in progress, samples of some of the soils in the area are collected for laboratory analyses. Soil scientists interpret the data from these analyses and tests as well as the field observed characteristics of the soil properties to determine the range of values for key soil properties for each soil. They also use these data to determine the expected behavior of the soils under different uses. Soil property data is organized and stored in a database, where it is used to generate soil interpretations for use and management. Interpretations for all of the soils are field tested through observation of the soils in different uses and under different levels of management. Special studies to document dynamic soil properties that are affected by use and management may be conducted (see chapter 9). Data are assembled from other sources as well, such as research information and field experience of specialists.

After survey staff locate and identify the significant natural bodies of soil in the survey area, they draw the boundaries of these bodies on a map and identify each as a specific map unit by name. Imagery showing trees, buildings, roads, and rivers is commonly used as a base map to help in locating boundaries accurately. Tonal shades and patterns on aerial photographs or digital images are used to indicate potential changes in vegetation, drainage conditions, parent materials, and other factors affecting surface reflectance. As digital mapping techniques are being increasingly integrated into mapping (see chapter 5), additional sources of information, such as multispectral bands, digital elevation models, and other data layers (such as geology), along with global positioning systems (GPS) are used to accurately locate map unit boundaries. Although the processes used in digital mapping techniques are different from nondigital conventional methods, the principles are the same.

In the United States, soil surveys vary in scale and in intensity of observations. The components of map units are designated by taxa in *Soil Taxonomy* (Soil Survey Staff, 1999) or as miscellaneous areas (i.e., nonsoil areas). In naming a map unit, soil taxa names (commonly a soil series name) are modified with phase terms (indicating surface texture, slope, flooding, stoniness, etc.) to convey information that is either more specific than the wider range of properties defined for the series (e.g., surface texture) or that represents a property outside of the soil itself (e.g., flooding). The phase commonly is a portion of the range of properties exhibited by the taxon. For example, a certain soil series may have slopes ranging from 3 to more than 60 percent but the map units are shown with narrower ranges (e.g., 3 to 8, 8 to 15, 15 to 25) to provide information that is useful in managing the soils in the area.

Historically, soil surveys have classified entire polypedons and grouped their properties for interpretative output as vector maps (polygons). Some contemporary surveys classify only certain soil properties, such as surface rock fragment cover, and output the information as raster maps, in which each pixel represents a specific value of the property. With these maps, commonly called "soil property maps," the user can decide how to group or aggregate the information for their needs. Strictly speaking, maps of individual soil properties are not synonymous with soil surveys, which by definition delineate natural soil bodies.

Soil Mapping and the Scientific Method

Soil mapping uses the scientific method, in which the scientist must: (1) develop questions, (2) generate hypotheses that answer those questions, (3) test the hypotheses, and (4) confirm or reject the hypotheses. After a tentative delineation of a soil body is drawn on an aerial photo or digital image, the soil mapper (step 1) questions what type of soil exists within that delineation. Typically, the delineation follows a landscape feature, such as a large flood plain or a ridge summit. Based on previous knowledge about the soils of the region, the mapper (step 2) develops hypotheses, such as the Alpha and/or Beta series occurs within the delineation. The mapper (step 3) tests those hypotheses by augering, backhoe trenching, or observing natural exposures and (step 4) confirms or rejects each hypothesis. After documenting the results, the mapper returns to step 1 (develops questions) and repeats the process for a neighboring area. This process allows the soil scientist to map soils efficiently. Rather than making a large number of observations on a regular grid pattern to discover the kind of soil present, the mapper selects a limited number of strategically located points in the landscape to make observations. The observations confirm or reject the previously developed model. The mapper essentially is predicting the soil beforehand and only making an observation to confirm the prediction, rather than discovering the soil only after each observation is made. As long as the model is accurate, relatively few observations are required to make an accurate map (Hudson, 1992).

The scientific method is also used when investigating soil genesis. Although soil mapping and soil taxonomic classes are based on quantifiable properties rather than soil genesis (Smith, 1963), it is nevertheless useful for the soil mapper to develop conceptual models about soil genesis throughout the mapping process (Arnold, 1965). The most useful is the "multiple working hypotheses" method, which is based on the premise that when a scientist creates multiple hypotheses for an observed feature rather than one hypothesis, they are less likely to develop a parental attachment to "their" hypothesis (Chamberlin, 1897). Instead, the scientist becomes engaged in finding evidence that disproves each of the competing hypotheses. The "working hypothesis" is the one that survives. This method of testing multiple hypotheses simultaneously not only enhances the quality of conceptual models but also lessens antagonistic debates between scientific colleagues (Platt, 1964).

Soil Maps

Historical Approach

Aerial photographs were used as the mapping base in most soil survey areas in the United States during the 20th century. Conventional panchromatic (black and white) photography, color photography, and infrared photography were used for remote sensing and as base maps for the soil survey. Information on the applicability of each type of base map and how the older map products were used is covered in the 1993 *Soil Survey Manual* (Soil Survey Division Staff, 1993).

Aerial Photographs

Even in the current digital age, the use of aerial photographs remains an effective means of mapping soils in areas where suitable digital imagery and data layers or the required skills, resources, or support for digital mapping techniques are not available. Chapter 5 covers the integration of digital soil mapping techniques in conducting soil surveys.

Aerial photographs are still a viable mapping base in soil survey. They provide important clues about kinds of soil from the shape and color of the surface and the vegetation. The relationships between patterns of soil and patterns of images on photographs for an area can be determined. These relationships can be used to predict the location of soil boundaries and the kinds of soil within them.

Aerial photographs using spectral bands not visible to the eye, such as color infrared, enable subtle differences in plant communities to be observed. Other spectral bands in the infrared are useful in distinguishing differences in mineralogy and moisture on the soil surface and also have better cloud penetration. These data must be interpreted by relating the visual pattern on the photographs to soil characteristics found by inspection on the ground.

Features, such as roads, railroads, buildings, lakes, rivers, and field boundaries, and many kinds of vegetation can be recognized on aerial photographs and serve as location aids. Cultural features commonly are the easiest features to recognize on aerial photos, but they generally do not coincide precisely with differences in soils, except in areas with significant anthropogenic alteration. Chapter 11 provides guidance on mapping human-altered landscapes and human-transported soil materials.

Relief can be perceived by stereoscopic study. Relief features are helpful in locating many soil boundaries on the map. Topographic maps also provide insight to relief, slope, and aspect. Relief also identifies many kinds of landforms commonly related to kinds of soil.

Many landforms (e.g., terraces, flood plains, sand dunes, kames, and eskers) can be identified and delineated reliably according to their shapes, relative heights, and slopes. Their relationship to streams and other landforms provides additional clues. The soil scientist must understand geomorphology (discussed in chapter 2) to take full advantage of photo interpretation.

Accurate soil maps cannot be produced solely by interpretation of aerial photographs. Time and place influence the clues visible on the photographs. Human activities have changed patterns of vegetation and confounded their relationships to soil patterns. The clues must be correlated with soil attributes and verified in the field.

Contemporary Approach

Digital imagery has replaced photographs as the mapping base in 21st century soil survey. The ability to overlay multiple imagery resources for comparisons, the ability to quickly adjust scale, and the use of raster-based soil maps have increased the speed of delivering soil survey products as well as the variety of products available. Customized soil survey products are enhanced by the choice of background imagery (e.g., color imagery and topographic imagery) used to display soil survey information. Methods for digital soil mapping and the products derived from digital imagery are discussed in chapter 5.

Sources of Apparent Error on Existing Soil Maps

Soil surveys in the United States. meet the technical standards and design requirements in place at the time they were completed. However, standards in use varied from State to State or regionally. In addition, standards evolved with increased knowledge about soils and changes in user needs. One should not assume that the soil survey data and maps completed many years ago, which did not have the benefit of recent evaluation and update, meet the standards and expectations of users today.

Soil survey mapping scale and map unit design considerations likely cause the most apparent errors on soil maps. Projects were designed to collect and document soil distribution and properties based upon user needs and were not more detailed than necessary. For low-intensity uses of the soil (e.g., grazing on native rangeland, native forests, watershed, and wildlife habitat), soil mapping was performed on a small-scale photo base of 1:48,000 to 1:63,560, or smaller. Areas of soil that were markedly different in use and management but too small to be delineated at the scale of mapping were described as inclusions in map units or denoted by a spot symbol on the map. When the mapping is presented at a larger scale, these areas may appear to be errors in the map.

Soil surveys in the U.S. were initiated with "memoranda of understanding" between National Cooperative Soil Survey (NCSS) partners and other local partners. These documents included agreed-to scheduled progress targets and completion date. The schedule dictated the scale of mapping and the mapping intensity or order. Map units were designed to meet specific user needs, and fieldwork was conducted to create soil maps that met those needs. If the user needs change due to changes in land use, the map unit design may not adequately meet the new needs. Soils with markedly different potentials or risks based upon use may not be adequately separated in mapping units.

Standards used in the soil correlation process set minimum extent requirements for both a map unit and a soil series included in the soil survey legend. Setting these limits was done prior to computerization to ensure that data and information would remain manageable. At the end of a project, map units and series that did not meet the minimum extent requirements were combined with the most similar map unit or component in the legend and the concepts were expanded to include these soils and areas.

Boundaries of the soil mapping legends generally coincided with county or State lines. Small areas of soils having a different bedrock geology, physiography, or major land resource area (MLRA) that crossed the political soil survey boundary (map legend boundary) were too small in extent to appear in the legend alone, so they were combined with the most similar map unit. When two adjacent survey areas are viewed at the join, fault lines may appear between the two surveys. Under the MLRA approach currently used to update soil survey in the U.S., these faults are being corrected.

Significant changes in the soil resource itself may have occurred since the time of soil mapping. Extensive anthropogenic activities, including mining, excavation, land leveling, and construction, remove or bury native soils. Because of natural processes, such as changes in stream courses, landslides, and volcanic eruptions, soil materials at the surface may differ from those identified on soil maps completed earlier. These changes are generally dramatic and easily recognizable on the landscape. Some, however, may be subtle (e.g., filling of wet areas, alterations to hydrology, and mechanical alterations such as deep ripping and deep mixing).

Other actual errors may be discovered on soil maps, including labeling errors done in the field and map compilation and publication errors. They should be documented and corrected.

Field Operation and Equipment

The efficient operation of a soil survey requires the use of certain kinds of equipment. The three major equipment needs are: (1) tools to examine the soil profile; (2) soil testing, measuring, and recording devices for mapping; and (3) transportation vehicles. While some of the equipment used in soil survey reflects new technology, such as tools for proximal sensing of soil properties (discussed in chapter 6), many of the basic tools for observing soils in the field have changed little in recent years. The 1993 *Soil Survey Manual* contains a detailed discussion and description of many of these items. Short descriptions of commonly used field tools are also provided in the *Field Book for Describing and Sampling Soils* (Schoeneberger et. al., 2012, pp. 8-5 and 8-6).

Tools for Examining and Testing the Soil

A soil scientist examines the soil often in the course of mapping. Examination of both horizontal and vertical variations is essential. The most commonly used tools are spades and soil augers. Augers are used in most areas for routine mapping. In some areas, however, a spade is used to examine the soil. In soils with no rock fragments, samples can be collected quickly and relatively easily using truck-mounted (fig. 4-1) or

Figure 4-1

A truck-mounted hydraulic probe used to quickly obtain soil profiles. The Giddings probe (shown) has the ability to collect a large- or small-diameter core sample, and extensions can be added to it for deep coring. Driver's side-mounted bull probes are preferred in some areas but are limited to collection of smaller diameter core samples. (Photo courtesy of Casey Latta) hand-operated probes. Backhoes and shovels are used to expose larger soil sections for examination, sampling, and photography. Where a probe or auger is regularly used for examining the soil, a large pit exposed by a backhoe (see fig. 4-2, left image) can be used to ensure map unit concepts are as predicted and have not strayed from the conceptual model developed.

Figure 4-2

Left image—A backhoe excavation providing a large view of the soil profile and improving access for description and sampling. Right image—Shoring, exit ramps, and other safety measures must be used to protect staff in deep trenches. (Photos courtesy of Wayne Gabriel)

Backhoes, however, have limitations. Cost as well as time to perform needed maintenance must be considered. Where available locally, renting a backhoe and operator only when needed may be an option. Some property owners do not want large equipment on their property. Operators must be trained to use the equipment efficiently, and safety standards must be met (see fig. 4-2, right image). Overhead and underground power lines, which pose electrical hazards, and other utilities must be located and avoided. Slopes may be too steep for safe operation of machinery. It is important to recognize soil properties that make trench walls prone to collapsing and thus dangerous for anyone in a pit. Designing backhoe trenches with benching, shoring, and exit ramps can improve safety.

Equipment for unique environments must be considered. Power equipment is commonly used to save time and effort. Vibracore samplers are used to obtain subaqueous soil samples several meters below the water surface. Devices such as core catchers are used to prevent the sandiest materials from falling out of the sample tube. Various small instruments can also be used to examine the soil, such as small handheld digital meters that determine salinity, soil reaction, sodicity, and soil nutrients. Proximal sensing tools, such as XRF meters, electromagnetic induction, and ground-penetrating radar, can also be used. See chapters 6, 10, and 11 for more information on tools suited to proximal sensing and unique environments.

Measuring and Recording Devices for Mapping

A handheld geographic positioning system (GPS) unit can assist in navigation and capture the location of soil descriptions. It can be indispensable as a navigation aide in remote or roadless areas. GPS provides both horizontal position in geographic coordinates and elevation. Most units can store and recall waypoints and so help workers identify and return to specific locations. Some provide background maps of geographic and cultural features to aid navigation.

A small digital camera is useful in capturing quality images of soil profiles and features, landscape settings, and vegetation and documenting land use and management. Smartphones, tablets, and some laptops have built-in cameras that can be used for capturing and storing images. If digital images are used as the mapping base, laptop computers or tablet PCs (provided they are sufficiently ruggedized and suited to outdoor viewing) can be used to display and annotate maps.

Waterproof data loggers can be installed at some study sites to automatically collect measurements of air and soil temperatures, water potential, and more. These data can be collected over 1 or more years as needed and summarized to characterize site conditions for classification and interpretation.

Transportation

Field operations in soil survey require transportation of workers, equipment, supplies, and soil samples. Vehicles are provided to the soil survey team for their daily operations. The time spent by soil scientists traveling to and from the field can be lengthy and mainly unproductive. Enough vehicles are provided to keep travel time as short as possible.

Additional equipment used for special purposes or for short periods is typically rented or supplied as needed. A passenger van, for example, may be furnished by one of the soil survey project's partners during a field review. Some vehicles must carry power equipment or pull trailers. All vehicles should be suited to the needs of the survey area, whether it be for use off road or in paved areas; to carry workers efficiently, comfortably, and safely; to hold the regularly used equipment; to accommodate an extra load; or to protect workers and equipment from adverse weather.

Specialized vehicles are needed in some areas. Aircraft, particularly helicopters, are used in some soil surveys to transport workers and equipment and to provide broad views of landscapes and vegetation. Aircraft are useful for photographing landscapes, soil patterns, and land use. Availability, cost, and lack of conventional landing sites are the main limitations to using aircraft. Snowmobiles provide winter access where travel is impossible or impractical in other seasons. Tracked vehicles, trail bikes, and all-terrain vehicles (ATVs) may be needed in areas that otherwise can be reached only by walking. Pack horses may be the only viable means of transporting people and equipment in wilderness areas. Marsh buggies with large buoyant tires and airboats are used in swamps and marshes. Canoes and small boats may be used to navigate waterways or to access areas consisting of numerous islands. Shallow draft boats are useful in conducting soil surveys in areas consisting of subaqueous soils (see chapter 10). Specialized vehicles must be reliable in remote areas.

Costs of buying or renting equipment, maintaining the equipment, and training operators can be high. Time is needed for transport, maintenance, and training. Some equipment is hazardous to operate. In addition, sensitive ecosystems may be damaged by the equipment.

Soil Identification and Classification

In soil surveys, the individual parts that make up the soil continuum are classified. The classes are defined for bodies of soil of significant kinds and extent. The taxonomic classes are conceptual. Their definitions are based on the knowledge of soils as they occur in nature and the understanding of the genetic processes responsible for their formation. The taxonomic classes themselves are not real soils, but they relate to their representatives in nature—the pedon and the polypedon.

Pedon

A pedon is the smallest body of one kind of soil that is large enough to represent the nature and arrangement of horizons and the variability in the other properties. It lacks boundaries with neighboring pedons (Soil Survey Staff, 1999). It is a unit of observation, sampling, and classification.

A pedon extends down to the lower limit of a soil, through all genetic horizons and, if the genetic horizons are thin, into the upper part of the underlying material. It includes the rooting zone of most native perennial plants. For purposes of most soil surveys, a practical lower limit of the pedon is bedrock or a depth of about 2 m, whichever is shallower. A depth of 2 m allows a good sample of major soil horizons, even in thick soil. It includes much of the volume of soil penetrated by plant roots, and it permits reliable observations of soil properties.

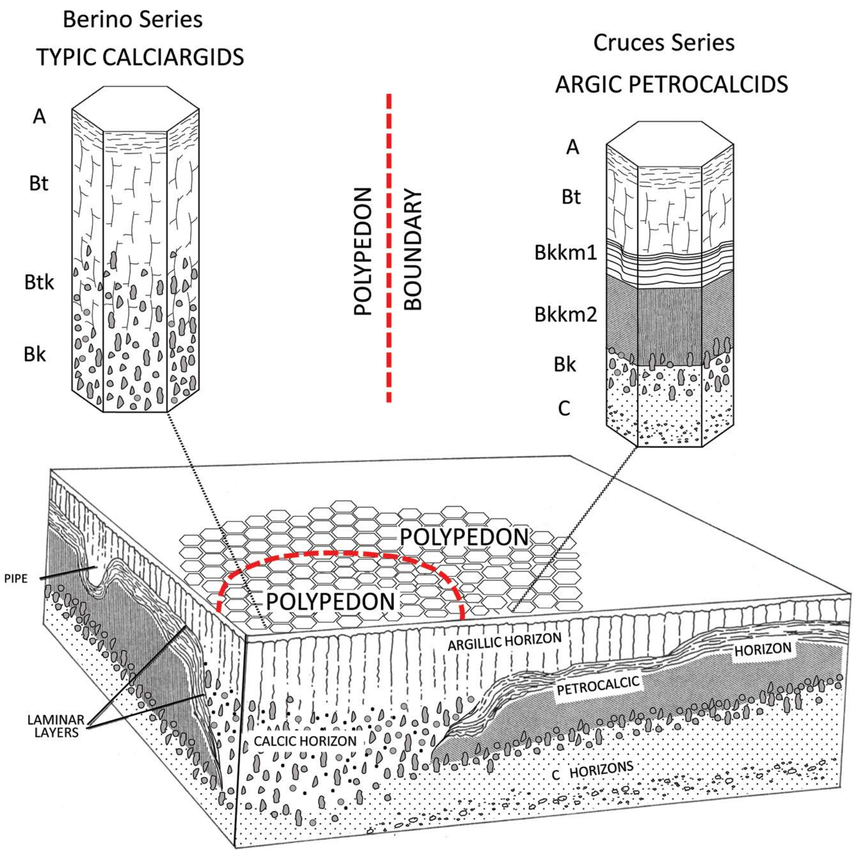
The surface of a pedon is roughly polygonal and ranges from 1 to 10 m^2 in area, depending on the nature of the soil's variability. Where the cycle of variations is less than 2 m and all horizons are continuous and nearly uniform in thickness, the pedon has an area of approximately 1 m^2. Where horizons or other properties are intermittent or cyclic over an interval of 2 to 7 m, the pedon includes one-half of the cycle (1 to 3.5 m). If horizons are cyclic over an interval greater than 7 m, each cycle is considered to contain more than one soil. The range in size, 1 to 10 m^2, permits consistent classification by different observers where important horizons are cyclic or repeatedly interrupted over short distances.

Polypedon

A pedon by itself is too small to be the unit of soil mapping because it cannot account for features such as slope and surface stoniness. In addition, it is too small to embody the full range of variability occurring within a soil series. Instead, the polypedon is used to define a soil series and is the unit of soil mapping. It is the three-dimensional soil body or soil individual that is homogeneous at the soil series level of classification. It is big enough to exhibit all the soil characteristics considered in the description, classification, and mapping of soils (fig. 4-3).

The concept of the polypedon is, from a practical standpoint, more or less equivalent to the *component* in soil mapping, but with one technical difference. Since the polypedon is defined as being homogenous at the series level of classification, each pedon making up the polypedon must fall within the class limits for all the properties (texture, color, reaction, thickness, etc.) of that series. When the limits of taxa are superimposed on the pattern of soil in nature, areas of taxonomic classes rarely, if ever, coincide precisely with mappable areas. In contrast, the map unit component represents a miscellaneous area or a natural soil body that includes all of the pedons making up the polypedon, as well as other very similar pedons within the mapped area that are just slightly outside the property ranges assigned for the series. A polypedon and similar or non-contrasting soils (discussed later in this chapter) occur within the concept and boundaries of the map unit component. Soil map units may consist of one or more components.

Figure 4-3



Polypedons vary in size. This figure illustrates a small polypedon formed in a pipe through a petrocalcic horizon (Gile et al., 2003). It also illustrates the concept that pedons have no lateral boundaries with neighboring pedons, unlike polypedons, which do have boundaries with neighboring polypedons.

The polypedon represents the minimum unit of interpretation and soil management. If the boundaries of an individual polypedon are gradual and diffuse, the polypedon is virtually impossible to delineate because its properties are confined by the taxonomic class it represents (series) and these properties vary in a sinuous or continuous manner in either vertical or horizontal dimensions. Boundaries between map unit components, however, are commonly evident where the differences produce contrasting native plant communities or changes in properties that impact soil use and management. Boundaries of both map unit components and polypedons may be easily observed at discontinuities, such as erosional facies and geologic contacts, and following human alteration.

Polypedons link the real bodies of soil in nature to the mental concepts of taxonomic classes and are the basis of soil components used in mapping, interpreting, and managing soils.

Soil Map Units

Soil map units are designed to efficiently deliver soil information to meet user needs for management and land use decisions. Map units can appear as individual areas (i.e., polygons), points, or lines on a map. A map unit is a collection of areas defined and named the same in terms of their soil components, miscellaneous areas, or both (components and miscellaneous areas are described below). Each map unit differs in some respect from all others in a survey area and is uniquely identified on a soil map. A map unit description is a written characterization of the component within a map unit and the relationship of one map unit to another. Appendix 2 provides an example of a map unit description.

Soil map units consist of one or more components (defined below). A delineation of a map unit generally contains the major (dominant) components included in the map unit name, but it may not always contain a representative of each kind of minor component. In older soil surveys, minor components were neither described nor interpreted in detail and were referred to as inclusions within a map unit. A dominant or major component is represented in a delineation by a part of a polypedon, a complete polypedon, or several polypedons. A part of a polypedon is represented when the phase criteria, such as slope, require that a polypedon be divided. A complete polypedon occurs if there are no phase criteria that require the subdivision of the polypedon or the features exhibited by the individual polypedon do not cross the limits of the phase. Several polypedons of a component may be represented if the map unit consists of two or more dominant components and the pattern is such that at least one component is not continuous but occurs as an isolated body or polypedon. Similarly, each minor component in a delineation is represented by a part of a polypedon, a complete polypedon, or several polypedons. Their extent, however, is small relative to the extent of the major component(s). Because soil boundaries can seldom be shown with complete accuracy on soil maps, parts and pieces of adjacent polypedons are inadvertently included or excluded from delineations.

Some map unit delineations may not contain any of the dominant components named in the map unit description but contain what are termed "similar soils." In most survey areas, there are soils that occur as mappable bodies but have very limited total extent within a specific survey area. They are typically included with other map units if, for all practical purposes, their soil interpretations are the same. The allowance of similar soils in map units is by design—it permits the number of map units and named components to be reduced without reducing the interpretative value of the soil map.

The kinds of map units used in a survey depend primarily on the purposes of the survey and the pattern of the soils and miscellaneous areas in the landscape. The pattern in nature is fixed, and it is not exactly the same in each delineation of a given map unit. In soil surveys, these patterns must be recognized and map units designed to meet the major objectives of the survey based upon known or projected user needs. It is important to remember that soil interpretations are made for areas of land and the most useful map units are those that group soils based upon their similarities.

Component

Within the context of a map unit, a component is an entity that can be delineated at some scale. It is commonly a soil but may be a miscellaneous area. Components consisting of soil are named for a soil series or a higher taxonomic class. Those that are miscellaneous areas are given an appropriate name, such as "Rock outcrop" or "Urban land." In either case, each component that makes up a map unit can be identified on the ground and delineated separately at a sufficiently large scale. Map unit components describe the properties of natural bodies of soils, or miscellaneous areas of nonsoil, in a particular landscape. Components can be major or minor in extent, depending upon the kind of map unit and percent composition. Designation of components as major or minor in soil databases is helpful for interpretive groupings. Typically, only major components are used in a map unit name.

Table 4-1 lists the kinds of map unit components used in soil survey. Soil components typically represent less than the full range of some properties allowed in a taxonomic class, which is defined by limits of key diagnostic properties. They may also differ from taxonomic classes and be slightly outside the class limits of some properties that define the taxa. Soils having properties that are slightly outside the defined taxonomic limits but that do not adversely impact major land uses are called similar soils. Map unit components are commonly a subset of the dominant taxonomic class or series in the delineation and similar soils. By identifying and naming components in map units, a soil scientist can quickly communicate interpretive information about a map unit and still indicate its complexity.

Table 4-1

Kinds of Map Unit Components Used in Soil Survey

Component kind	Description
Soil series	Most common component. It is the lowest categorical level of Soil Taxonomy.
Taxonomic categories above the series	Components given a taxonomic reference term that implies no specific range of properties beyond what is given in the map unit description.
Taxadjuncts	Components that are named for a soil series they resemble but have one or more differentiating characteristics that are outside the taxonomic class limits of that series. Their use and management is similar to that of the named soil series.
Miscellaneous areas	Components that are not soil as defined in *Soil Taxonomy* (such as Rock outcrop) or are bodies of soil that are no longer capable of supporting plants, such as soils heavily contaminated by toxic substances. Examples are given in table 4-2.
Phases of components	Components that are assigned a descriptive term to help distinguish between multiple components of the same taxonomic or miscellaneous area occurring within the same map unit legend or geographically associated map units.

Soil Series

The series represents a three-dimensional soil body having a unique combination of properties that distinguish it from neighboring series. The soil series concept was developed more than 100 years ago and somewhat followed the logic of the series as used to describe sediments in the geologic cross-section. Like the geologic formation, the soil series has served as the fundamental mapping concept. In geology, strata closely related in terms of their properties and qualities were members of a series in the sedimentary record. Initially, the soil series did not conform to a specific taxonomic class nor property class limits but rather to the predominant properties and qualities of the soil landscape, climate, and setting in which the soil occurred.

Today, the soil series category is the lowest level and the most homogeneous category in the U.S. system of taxonomy. As a class, a series is a group of soils or polypedons that have horizons similar in arrangement and in differentiating characteristics. The soils of a series have a relatively narrow range in sets of properties. Although part of *Soil Taxonomy*, soil series are not recorded in it. In the United States, they are in the Official Soil Series Descriptions database (Soil Survey Staff, 2016a). Appendix 1 provides an example of a soil series.

The soil series is not the object mapped in soil survey. Natural soil bodies are mapped and then described and classified. Each map unit soil component is correlated to a soil series or other taxonomic class. Soil series serve as a bridge between real soil bodies and conceptual taxonomic classes. They are an important tool for naming, remembering, and communicating information about soils. They also serve as a tool for transferring knowledge about soil genesis, properties, and interpretations from place to place, wherever a given soil series was correlated to a map unit component.

Soil series are differentiated on all the diagnostic features of the higher categories in Soil Taxonomy plus those additional and significant characteristics in the series control section (Soil Survey Staff, 1999). Some of the characteristics commonly used to differentiate series are the kind, thickness, and arrangement of horizons and their structure, color, redoximorphic features, texture, reaction, consistence, content of carbonates and other salts, content of humus, content of rock fragments, temperature, kinds and thickness of human-altered materials, and mineralogical composition. A significant difference in any one of these can be the basis for recognizing a different series. Very rarely, however, do two soil series differ in just one of these characteristics. Most characteristics are related, and generally several change together.

Some soils are outside the limits of any recognized soil series and have unique sets of properties. These are potential new series. When such a soil is first recognized, it is described and identified as a taxon of the lowest category in which it can be classified. A phase of that taxon can be used to identify a map unit. In some surveys, including virtually all detailed surveys, definitions need to be further refined. For these, the soil is proposed as a new series. The new series remains tentative until its properties can be described in detail, its extent determined, and any conflicts with established series resolved. If the tentative series remains through the correlation process, it is established as a new series at the time of final correlation. A taxonomic unit description includes the ranges in soil properties exhibited within the mapped areas for that taxonomic unit. The limits of these ranges are set for the taxonomic class, but generally the full range allowed by the taxonomic class is not exhibited in a survey area.

Taxa Above the Soil Series

The first level above the series is the family. Components mapped to the family level match the classification of a series, but not the series criteria. The name of a representative series belonging to the component taxonomic classification is used as the component name (e.g., Ezbin family). The component name represents the range in characteristics for many series within the family classification. Use of family-level components is generally limited to soil survey orders 3 and 4.

Components mapped to levels higher than the family use the classification as a reference term and may include the range in characteristics for many families within the referenced classification. An example is coarse-loamy Typic Cryaquolls. In this example, the higher taxa is the subgroup Typic Cryaquolls and it is modified by the family-level particle-size class term "coarse-loamy" to provide additional information. These components are used especially on small-scale maps in soil survey orders 3 through 5.

During a survey, the taxonomic system is tested and retested many times. The results of these tests are reported at field reviews and the field correlation. Problems in mapping or identifying soils and inconsistencies between the system and observed properties of the soils are recorded in field review reports and correlation memoranda. After appraising these reports, supervisory soil scientists bring any inadequacies to the attention of the office responsible for keeping the system up to date.

Taxadjuncts

Taxadjuncts are polypedons that have properties outside the range in characteristics of any recognized series and are outside higher category class limits by one or more differentiating characteristics of the series. A taxadjunct is given the name of an established series that is most similar in characteristics. These components classify differently taxonomically but have the same interpretations for use and management as the named series. Because the differences in properties between the named series and its taxadjunct are small and do not affect major interpretations, a new series is not established. The taxadjunct is treated as if it were a member of the named series, and its interpretations are similar to those for comparable phases of the series for which it is named. Differences from the established series are described. For example, a fine-silty map unit component differs slightly from an established fine-loamy series in only particle size, and no current soil series exist to accommodate the fine-silty classification. The fine-silty soil is correlated as a taxadjunct to the established fine-loamy series and a new series is not proposed.

Miscellaneous Areas

Miscellaneous areas are land that has little or no identifiable soil and thus supports little or no vegetation without major reclamation. Examples of miscellaneous areas are shown in table 4-2. The areas can be a result of active erosion, washing by water, unfavorable soil conditions, or human activities. Some miscellaneous areas can be made productive but only after major reclamation efforts. Map units are designed to accommodate miscellaneous areas, and most map units named for miscellaneous areas include areas of soil. If the amount of soil exceeds the standards for minor components defined for the survey, the map unit is named as a complex or association of miscellaneous area and soil. One must be careful in determining that an area is a miscellaneous area rather than a soil. For example, not all areas that are mined should be named "Mined land." If they are able to support vegetation and thus meet the definition of soil, they should be classified as soil. This is particularly important if it is possible to populate at least some major soil property data in the soil database and so provide meaningful interpretive information. The National Cooperative Soil Survey maintains an official list of miscellaneous areas and their definitions for use in the U.S. soil survey (USDA-NRCS, 2016).

Phases

Phase terms added to map unit component names convey important information about a map unit and differentiate it from other map units on the map unit legend. A property of a taxon that has too wide a range for the interpretations needed or some feature outside the soil itself that is significant for use are a basis for phasing map units. Phases commonly include only part of the range of features exhibited by a taxon within a soil map unit. Soil phases can be based on attributes, such as frost hazard, character of the deeper substratum, or physiographic position, that are not characteristics used to identify taxa but nevertheless affect use and

Table 4-2

Miscellaneous Areas Used as Map Unit Components

Area	Description
Badland	Moderately steep to very steep barren land dissected by many intermittent drainage channels in soft geologic material. Ordinarily, it is not stony and occurs in semiarid and arid areas.
Beaches	Sandy, gravelly, or cobbly shores washed and rewashed by waves. The areas may be partly covered with water during high tides or storms.
Chutes	Elongated areas on steep mountain slopes that lack vegetation and have exposed bedrock, rock fragments, and woody debris. Avalanche or mass movement activity is evident.
Cinder land	Loose cinders and other scoriaceous magmatic ejecta. The water-holding capacity is very low, and trafficability is poor.
Dams	Artificial structures that are oriented across a watercourse or natural drainage area for the purpose of impounding or diverting water.
Dumps	Areas of smoothed or uneven accumulations or piles of waste rock and general refuse. “Dumps, mine” is an area of waste rock from mines, quarries, and smelters.
Dune land	Unstable sand in ridges and intervening troughs that shifts with the wind.
Glaciers	Large masses of ice formed by the compaction and recrystallization of snow. The ice front may be advancing or retreating. Areas may include incidental amounts of soil or rock.
Gullied land	Areas where erosion has cut a network of V-shaped or U-shaped channels deep enough to inhibit or prevent crossing.
Lava flows	Areas covered with lava. Most flows have sharp, jagged surfaces, crevices, and angular blocks characteristic of lava. Others are relatively smooth and have a ropy, glazed surface. A small amount of earthy material may occur in a few cracks and sheltered pockets.
Mined land	Areas that are significantly altered by mining activities. Soil material and rock have been moved into, out of, or within the areas designated. Because access to mined land may be limited by permissions or hazardous materials, identification of soil components can be difficult or impossible.

Table 4-2.—continued	
Area	**Description**
Oil-waste land	Areas where liquid oily wastes, principally saltwater and oil, have accumulated. They include slush pits and adjacent areas affected by the liquid wastes. The land is barren, although some of it can be reclaimed at high cost.
Pits	Open excavations from which soil and commonly underlying material have been removed, exposing either rock or other material. Examples are “Pits, mine,” “Pits, gravel,” and “Pits, quarry.”
Playas	Barren flats in closed basins in arid regions. Many areas are subject to wind erosion and many are saline, sodic, or both. The water table may be near the surface at times.
Riverwash	Unstabilized sandy, silty, clayey, or gravelly sediment that is flooded, washed, and reworked frequently by rivers.
Rock outcrop	Exposures of bare bedrock other than lava flows and rock-lined pits. If needed, map units can be named according to the kind of rock, e.g., “Rock outcrop, chalk,” “Rock outcrop, limestone,” and “Rock outcrop, gypsum.” If small, they can be identified by spot symbols on maps.
Rubbleland	Areas of cobbles, stones, and boulders commonly at the base of mountains or left on mountainsides by glaciation or periglacial processes.
Slickens	Accumulations of fine textured material from placer-mine and ore-mill operations. They may have undergone chemical extractions. They are typically confined in constructed basins.
Urban land	Land mostly covered by streets, parking lots, buildings, and other structures of urban areas.
Water	Streams, lakes, ponds, and estuaries that are covered with water, deep enough or moving, that growth of rooted vegetation is precluded. Many areas are covered with water throughout the year.

management. Common phases are slope, surface texture, flooding and ponding, surface fragments, degree of erosion, and climate (see table 4-3 in the “Naming Map Units” section). Overlying water depth is used as a phase term for some subaqueous soils. Phases such as “filled,” “graded,” or “landscaped” are used for some map units consisting of soils that formed in human-altered or human-transported material.

Phase terms are devised and used as needed to differentiate map units. The usefulness of each phase must be repeatedly tested and verified during a survey. Separate phases of a taxon must differ significantly in behavior. If no useful purpose is served by separating them in mapping, similar phases of different taxa may be combined and the combination described. The interpretations prepared during the course of a survey provide evidence of similarities and differences among map units.

The justification for most phases rests on the behavior of the soils under various uses. At least one statement about soil behavior must be unique to each phase of a taxon, and the differences of soil properties must exceed normal errors of observation. The use of phase terms is described in greater detail in the section “Naming Map Units” below.

Classes

Classes of soil properties are not necessarily used directly as phases. Defined class limits of properties are designed for a convenient description of soil, but they can also be used to define phases of soil map units in some cases. For example, a map unit may be named as a moderately saline phase to distinguish it from another map unit with the same name but whose soils have no significant salinity. However, property class terms are not useful for all soils. Distinctions significant for one kind of soil are not significant for every other kind. Any single property is significant only through its interactions with other properties.

Kinds of Map Units

Soils differ in size and shape of their areas, in degree of contrast with adjacent soils, and in geographic relationships. Four kinds of map units are used in soil surveys: consociations, complexes, associations, and undifferentiated groups.

In most map units, areas of soil occur that do not meet all of the taxonomic criteria of the soil (series or higher taxa) used to name the map unit. However, because these soils have properties similar to those of the named soils and interpret similarly for the dominant land uses, they are included as part of the named component. They are referred to as similar or non-contrasting soils. Conversely, minor components and unnamed soils which interpret differently for major uses, whether they are well suited (less limiting) or poorly suited (more limiting), are called dissimilar or contrasting soils.

The total amount of dissimilar minor components in a map unit generally does not exceed about 15 percent if they are limiting and 25 percent if they are nonlimiting. A single dissimilar limiting component generally does not exceed 10 percent if it is very contrasting.

In most cases, soil map units can be delineated as polygons. However, in some cases a polygon cannot be drawn to conform to cartographic standards due to size or shape constraints. In these cases, lines or points may be used to designate map units. If this is necessary, the narrow width or small size is included in the map unit description to indicate the nature of the soils on the landscape.

Consociations

In a consociation, delineated areas are dominated by a single soil component (or miscellaneous area). Commonly, at least one-half of the pedons in each delineation are of the same soil taxa as the named soil. The remainder of the delineation mostly consists of soil so similar to the named soil that major interpretations are not significantly affected. The map unit component thus consists of soil meeting the criteria for the taxonomic class (series or higher taxa) used to name the map unit plus similar soils. The soil in a consociation may be identified at any taxonomic level.

A consociation that is named for a miscellaneous area (such as Rock outcrop) dominantly consists of that kind of area, and any minor components present do not significantly affect the use of the map unit. Generally, less than about 15 percent of any delineation is soil or less than about 25 percent is other kinds of miscellaneous areas. Percentages may vary, depending upon the kind of miscellaneous area and the kind, size, and pattern of the minor components.

Complexes

Complexes consist of two or more dissimilar major components that occur in a regularly repeating pattern or in an unpredictable pattern. The major components of a complex cannot be mapped separately at a scale of about 1:24,000 (fig. 4-4). Typically, each major component occurs in each delineation, although the proportions may vary appreciably from one delineation to another. The major components are sufficiently different from each other in morphology or behavior that the map unit cannot be a consociation.

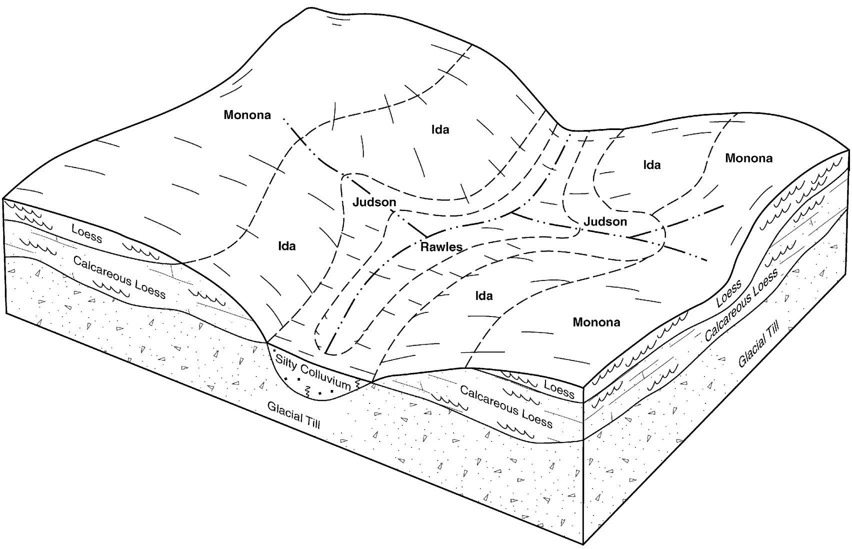
Figure 4-4

An area that meets the definition of a soil complex—the major components cannot be mapped separately at a scale of about 1:24,000. The bottom photo shows the profile of the Bluepoint series (Typic Torripsamments) that has formed as a coppice dune. The middle photo shows the distribution of the coppice dunes on the eroded phase of the Rotura series (Typic Petroargids). The top photo shows a landscape of the Bluepoint-Rotura complex in southern New Mexico.

Associations

Associations consist of two or more dissimilar major components occurring in a regular and repeating pattern on the landscape. The major components of an association can be separated at a scale of about 1:24,000, but due to land use or user needs, the map unit design integrates the predictable and repeating pattern of soil occurrence. Many general soil maps use soil associations because they are at scales much smaller than 1:24,000 and can depict only the characteristic landscapes of associated soils, not the individual soils (fig. 4-5). The major components are sufficiently different in morphology or behavior that the map unit cannot be a consociation.

Figure 4-5



Block diagram depicting the relationship of the soils in the Monona-Ida-Judson association in the general soil map (published scale of 1:125,000) of Woodbury County, Iowa (USDA-NRCS, 2006). Because a general soil map cannot show the location of each soil making up an association, accompanying diagrams such as this are commonly used. Monona soils are classified as Typic Hapludolls, Ida soils as Typic Udorthents, Judson soils as Cumulic Hapludolls, and Rawles soils as Oxyaquic Udifluvents.

Undifferentiated Groups

An undifferentiated group is a map unit of dissimilar soils that are not consistently associated geographically and, therefore, do not always occur together in the same map unit delineation. These components are included in the same named map unit because use and management are the same or very similar for common uses. Generally, some common feature outside of the soil itself, such as steepness, stoniness, or flooding, determines use and management. If two or more very steep soils that are geographically separated are so similar in their potentials for use and management that defining two or more additional map units would serve no useful purpose, they may be placed in the same unit. Every delineation has at least one of the major components and some may have all of them.

Minor Components Within Map Units

In all soil surveys, virtually every delineation of a map unit includes areas of soil components or miscellaneous areas that are not identified in the name of the map unit. Many areas of these components are too small to be delineated separately. Examples are small areas of steeper slopes or small areas of wet soils in an upland map unit. The location of some components cannot be identified by practical field methods. Some minor components are deliberately included in delineations identified as another map unit to avoid excessive detail on the map or the legend. These soils of very limited extent were referred to simply as "inclusions" in mapping before the mid-1990s, but are now identified as minor components and correlated to the lowest level of classification, as appropriate. Minor components are not indicated in the map unit name, but they are observed and documented in the map unit description.

Minor components reduce the homogeneity of map units and may affect interpretations. The objective is to define map units that contain as few as possible minor components that behave differently from the named components. Map units must be defined, recognized, and delineated consistently in the field.

The number of minor components reflects the taxonomic purity of map units. This number and the degree that contrasting minor components differ from the major components can be used to estimate the interpretative purity of map units. The actual amount of minor components is estimated from observations made during the survey. Adjustments in mapping and map unit design may be needed.

In the definition of map units, a scientist must judge the effects of minor components on management against the amount of work required to minimize the number of minor components. Determining the impact of the differences between the major and minor components is useful. If differences are small, the components are compared as similar. If differences are large, the components are contrasted as dissimilar.

Similar components are alike in most properties and share diagnostic properties and limits. Interpretations for most common uses are alike or reasonably similar and the interpretative value of the map unit is not affected. In contrast, dissimilar components differ appreciably in one or more properties, and the differences are great enough to affect major interpretations. Some dissimilar components are limiting and others are nonlimiting relative to the interpretations being considered.

If a minor component does not restrict the use of entire areas or impose limitations on the feasibility of management practices, its impact on predictions for the map unit is small. Minor components that have restrictions on use less severe than those of the dominant soil do not adversely affect predictions about the unit as a whole. They may even be beneficial. Such minor components are nonlimiting, and the interpretative purity of a map unit for most interpretations is not altered. For example, including small areas having slopes of 4 to 8 percent in an area having slopes mainly of 15 to 25 percent has no adverse effect on use of the area for most purposes. However, if the minor component has significantly lower potential for use than the dominant component in the map unit or affects the feasibility of meeting management needs, a small amount in a map unit can greatly affect predictions. These are the most critical minor components because they decrease the interpretative purity of map units. Even a small area having slopes of 15 to 25 percent in a map unit dominated by slopes of 4 to 8 percent can seriously affect the use of the area for many purposes. Even small minor components of wetter soils (such as Typic Epiaqualfs) in areas of upland soils (such as Aquic Hapludalfs) may control and limit the uses of the dominant soil component.

Soils that cannot be used feasibly for the same purposes as the surrounding soils are especially important to identify. They are delineated separately if the map scale is small enough and if delineating them will improve the usefulness of the map for the major anticipated uses. Areas too small to delineate may be identified and located on the map by special symbols.

Limiting Dissimilar Soils

Standards of purity are adjusted according to the precision required by the survey objectives. Generally, all delineations contain soils other than those identified in the map unit name. These minor components reduce purity. Different kinds of minor components, however, have different effects on the value of the map for use. The minor components that most detract from purity are those that are distinctly more limiting for use than the named soil. These are called limiting dissimilar soils. A soil may be a limiting dissimilar soil for some uses but not for others. The survey objectives must be considered when assigning limiting dissimilar soils. Not only the amount of limiting soils but also the size of their individual areas is important. Soil survey standards for both are set at levels that do not seriously detract from the validity of interpretations based on the named soil.

Standards of purity are attained by adjusting the field operations. For example, if the standards require that areas of limiting dissimilar soils as small as 0.1 ha be delineated, the area must be traversed at intervals close enough to locate areas that small and the soil must be examined at enough places along each traverse to detect them.

Designing and Documenting Map Units

Designing Map Units

Well designed map units are based on accurate soil-landscape models. They can be consistently associated with features observable on the surface (e.g., vegetation and geomorphic position) and consistently delineated by the survey team. Initial investigations identify the pattern of occurrence for each component making up the map unit. In most cases, well designed map units require a relatively few number of observations to delineate accurately.

Knowing the Parameters

Guidance documents (such as a memorandum of understanding or other project plan) outline considerations for the order of mapping, scale of mapping, minimum size delineation, base imagery (if used), documentation requirements, and specific interpretive needs of the user. The survey team is responsible for collecting complete and accurate soil data, assessing the complexity of the soil landscape, and designing map units that support land use decisions and meet the objectives of the survey project. If the information is too broad or too complex, the objectives of the survey will not be met.

While studying the soil patterns in different landscapes, soil scientists must keep in mind how best to relate the patterns observed to the appropriate map units. They must determine the kinds of map units, the level of soil taxa, and the phases needed to satisfy the survey objectives. By definition, a map unit differs from all others in the survey area and should be uniquely identified. This requires many judgements and hypothesis testing. Every map unit that is tentatively identified is evaluated by three tests: (1) Does it capture the characteristic signature in the landscape that can be recognized from remote sensing imagery or field observation? (2) Is it recognizable and repeatable for consistent mapping? (3) Is it needed to meet the objectives of the survey?

Delineating the Areas

The landscape is partitioned either in the field or using remotely sensed data. The first step is to group areas having the same soil-forming factors (chapter 1) and known catenas or conceptual models of related soils. This premapping step groups defined landscapes, landforms, geology, vegetation, and climatic areas. Areas that have these same repeating patterns are delineated and labeled as the same map unit. It is recommended that broad groupings are established first. The lines can be adjusted as the survey team completes fieldwork to verify map units and refine concepts.

Most Important Soil Line

Designing map units to indicate significant differences in behavior among soils is particularly important for meeting the current objectives of a survey. Map units separated according to differences in geomorphic processes (e.g., parent material, relief, and time) are considered the most important soil lines on the landscape. These lines should be the first delineated on a map. Indicating differences in geomorphic processes is important, even if no immediate differences in interpretations are known. Differences in soil properties that do not affect current interpretations may be important in the future. Too many delineations may greatly reduce the immediate usefulness of a soil map. The potential benefit of extra delineations (the value of the additional information) must be weighed carefully against the costs incurred in making additional separations. Every soil survey is designed to record knowledge about soils; however, this does not mean that the soil map must show the location of every kind of soil in a survey area or that the publication must record everything that is known about the soils. Capturing and managing all observations of soil data on maps, even if the data is not used for publication, is invaluable in later analysis to develop new maps or update soil information.

Defining the Components

The objectives of a survey determine the kind of map units and the kind of components used to define the map units (see table 4-1).

Taxonomic classes provide the framework upon which the basic sets of soil properties distinguishing soil map units are defined. They summarize an immense amount of research and experience related to the significance of soil properties and combinations of properties. They provide predefined sets of soil properties that have been tested for genetic relationships and interpretative value. Taxa provide a firm base for recognizing the components of potential map units in an unfamiliar area. Using established taxa is much easier than independently sorting out sets of properties and determining significant class limits.

Within each survey, soil maps can be designed with components correlated to a taxonomic level that reflects narrowly or broadly defined ranges of soil properties. In addition, map units can be designed with different compositions of major and minor components. Design flexibility allows the development of map units that will be useful for the purposes of a specific survey while maintaining as much uniformity in mapping as possible.

Traverses

Traverses are used to identify different components on a landform. The observation points along a traverse can be any distance apart. The distance is adjusted to the direction and scale of the soil boundaries and the variability of the important properties in each component. Sites for each observation are chosen to represent specific areas on a landform. For example, one recommended way to lay out a traverse in a field is to travel in a direction perpendicular to local drainage patterns. The soil components can then be documented in a swale where it is darkest, on a ridge where it is lightest in color, and also in the footslope and backslope positions (for observations of transitions between areas). Once the soil component is known for each position, a landform model can be developed for use in similar areas throughout the survey area.

Transects

Transects are used to determine the composition and design of map units. They have fixed length intervals between observation points. Observations made at points along a transect are typically identified as belonging to a particular taxon, or soil component, but can also be a combination of properties, such as depth, thickness, color, or vegetation.

When selecting delineations for transecting, it is essential to eliminate bias by stratifying transects randomly. One simple method is to separate the survey into several subdivisions and conduct transects within each subdivision. The different land uses (e.g., cropland and forestland) in each delineation of a map unit should be considered, and transects should be conducted in map units under each land use. Transects must be positioned to encounter the maximum variation in each delineation. The transect should be oriented so that the line does not follow a contour around a hill. Transects should go up and down the hill and across drainages.

Systematic variation is quantified and more easily understood with a transect. A map unit complex consisting of a soil component in concave positions and another soil component in convex positions is an example of a map unit exhibiting systematic variation. Interval spacing in the transect must be small enough to capture the variability of the landform. Narrow map units can be problematic because a straight line transect may not fit or may miss the variability visually observed. In such cases, measured line segment transects can be used to ensure all components are captured and quantified. Typically, only a small percentage of the map unit delineations contain transects. As the order of survey increases, the length and intervals in a transect also increase. In all cases, transecting is not the same as line mapping used to determine the placement of map unit boundaries on a landform.

Random variation (i.e., variation that is not understood and therefore cannot be readily explained) can also be quantified using transects. Areas containing soil properties that are not readily observed or explained, as in stratified layers of alluvium or depth to bedrock on a loess-covered basalt plain, are well suited to grid or stratified random transects. Random variation methods for transecting can also be used to accurately quantify components having systematic variation. Methods designed specifically to document systematic variation transecting should not be used to quantify components having random variation.

Other statistical methods to determine composition, such as Latin hypercube sampling, are employed in digital soil mapping techniques (see chapter 5). Site selection using digital techniques can be used when digital mapping is performed. Latin hypercube sampling is especially useful if the field investigator is inexperienced or lacks the intrinsic knowledge of the landscape and soil patterns.

Naming Map Units

A map unit is uniquely named to distinguish it from all others in the survey area. Different conventions are used for each of the four kinds of map units so that the kind of unit is easily recognizable. In general, names are as short as possible. Map unit names typically include the named major components, both soil and nonsoil, that occur in the map unit. Miscellaneous areas are named if they occur as a major component. Commonly an extra term, such as surface texture, which is not needed to distinguish a phase from all others in the survey, is used so that comparable phases in other areas have the same name.

Phases are groupings created to serve specific purposes in individual soil surveys. They can be defined for any class or classes of any category. Table 4-3 lists some commonly used phase terms. Other terms can be developed as necessary. The phase classes are helpful in describing the soil phases that are important for the survey. Differences in soil or environmental features that are significant to use and management or soil behavior are the basis for designating soil phases.

Any property or combination of properties that does not duplicate class limits for a taxon can be used to differentiate phases, and any value of a property can be set to divide phases. The choice of properties and limits are determined by the purpose of the survey and by how consistently the phase criteria can be applied. Because objectives differ from one soil survey to another, limits and ranges of a property or attribute may also differ from one survey to another. In general, phase criteria are given a smaller range where soil use is intensive (as for irrigated farming or urban development) and a larger range where soil use is extensive (as for forestry or grazing).

For detailed surveys, decisions must be made about what criteria to use to recognize phases of soil components, how broadly or narrowly to define the phases, and whether similar phases of different components have interpretations similar enough that they can be combined. Phases are used to convey important information about a map unit and to differentiate it from other map units in the legend. For less-detailed surveys, decisions must be made about how the complexities of soil in large areas can be best identified and represented for purposes of the survey, what combinations of soils characterize useful and mappable units, what taxonomic level should be used in naming map unit components, and which phases contribute to the usefulness of the map units.

The names of soil taxa, along with one or more modifying terms, are used to identify the soils in map units. For example, the name "Tama silt loam, 2 to 5 percent slopes" indicates that soils of the Tama series (an Udoll) are dominant in that map unit. The names of taxa of higher categories are also used in map unit names, especially on small-scale maps. For example, "Udolls, rolling" identifies a map unit consisting dominantly of soils of the Udoll suborder, which includes Tama and other series.

As methods of measuring soil properties are refined, as experience in the field increases, and as use and management requirements are

Table 4-3

Phases Most Commonly Used in Naming Soil Map Units

[Terms are listed in preferred order of occurrence if more than one phase term is used.]

Phase group	Phase usage
Surface texture	USDA surface texture name
Deposits on the surface	*Overblown, wind hummocky,* and *overwash*
Fragments	Size and quantity classes, including *gravelly, cobbly, stony,* and *rocky*, or *artifactual* (anthropogenic) and appropriate modifier of *non, very,* or *extremely*
Slope	Expressed as percent or a descriptive slope class, such as *nearly level, gently sloping (undulating), strongly sloping (rolling), moderately steep (hilly), steep,* and *very steep*
Depth	*Shallow* or *deep*, and appropriate modifier (such as *moderately* or *very)*
Substratum	Contrasting material as base of named soil (e.g., *sandy substratum, gravelly substratum, saline substratum*)
Soil water state	Reference to water table, drainage classes, wetness, flooding, or ponding or to artificial drainage (*drained)*
Salinity	*Nonsaline* through *strongly saline*
Sodicity	*Sodic*, with modifier as needed (e.g., *strongly sodic*)
Physiography	Landscape or physiographic term, as appropriate
Erosion	Degree of erosion, from *slightly eroded* through *severely eroded,* and *gullied*
Thickness	Thick or thin surface horizon or subsoil (e.g., *thick surface, thin solum*)
Climate	Precipitation and temperature variation (e.g., *high precipitation, cool*)

intensified, progressively narrower ranges in soil properties can be recognized or established. Narrow ranges of properties should not be established just because methods permit it. Unnecessary separations take time to delineate consistently, and they make the survey difficult to use. However, not separating two significantly different, mappable units makes a survey less useful. The significance of each map unit in meeting the objectives of the survey must be constantly evaluated during the mapping process.

Orders of Soil Surveys

All soil surveys are made by examining, describing, and classifying soils in the field and delineating their areas on maps. Some surveys are made to serve users who need precise information about the soil resources of areas a few hectares or less in size. These surveys require refined distinctions among small, homogeneous areas of soil. Others are made for users who need a broad perspective of heterogeneous, but distinctive, areas thousands of hectares in size. A soil survey made for one group of users may not be useful for another group.

The elements of a soil survey can be adjusted to provide the most useful product for the intended purposes. Different intensities of field study, different degrees of detail in mapping, different phases or levels of abstraction in defining and naming map units, and different map unit designs produce a wide range of soil surveys. Adjustments in these elements form the basis for differentiating five orders of soil surveys. Table 4-4 is a key for identifying orders of soil surveys.

Recognition of these different levels of detail is helpful in communicating information about soil surveys and maps, even though the levels cannot be sharply separated from each other. The orders are intended to convey the level of detail used in making a survey, the scale used to delineate map units, and how general the map units are. They also indicate the general levels of quality control that are applied during surveys. These levels affect the kind and precision of subsequent interpretations and predictions. The orders differ in the following elements:

- The soil survey legend, including:
    - the kinds of map units (consociations, complexes, associations, and undifferentiated groups) and
    - the kinds of soil taxa used in identifying the map unit components (soil series, families, subgroups, great groups, suborders, orders, and phases of them);
- The standard for purity (in composition or probability) of delineated soil areas, including:

  - the minimum area of a limiting dissimilar soil that must be delineated separately and thus excluded from areas identified as another kind of soil, and
  - the maximum percentage of limiting dissimilar minor components that is permissible in a map unit;
- The field operations necessary to identify and delineate areas of the map units within prescribed standards; and
- The minimum map scale required to accommodate the map units of the legend, the standards of minimum composition, and the map detail justified by field methods.

Mapping legends are designed to provide the degree of refinement of map units required by the objectives of the survey. A map unit can be identified as a consociation (an area dominated by a soil component of a single taxon, such as a series or suborder) or as a group (geographic mixture) of taxa, such as an association or complex. A group may be more heterogeneous, and less refined, than a consociation at the same level of classification. A soil series has a much more narrowly defined set of soil properties than a suborder and, therefore, is a more refined distinction. Thus, phases of soil series are used as map unit components if users need more precise information about small areas of soils. Phases of any category in Soil Taxonomy might be used as soil map unit components if only a very broad perspective of the soil resources of very large areas is needed.

Scale and Order of Mapping

The order of a survey is commonly reflected in the scale of mapping, but not determined by it. Rather, the order of a survey is determined by the field procedures used to identify soil components and place map unit boundaries, the minimum permissible size of map unit delineation, and the kind of map unit to which soil components are aggregated. Where soil maps are available in digital form, computer software allows users to change the map scale for display purposes. The ability to enlarge a map in this way can lead to misunderstanding the accuracy and level of detail on the soil map. The scale used to make the survey is the scale that must be used to display the mapping. See the 1993 *Soil Survey Manual* (Soil Survey Division Staff, 1993) for a discussion on scale and map legibility.

Digital soil mapping techniques (discussed in chapter 5) augment field procedures and remote sensing in identifying soil map components and placement of map unit boundaries. The benefits of digital soil mapping increase with increasing order of soil mapping.

Table 4-4

Key for Identifying Orders of Soil Surveys

Order and level of data needed	Field procedures	Min. size of map units *(ha)*[1]	Typical components of map units	Kind of map units[2]	Appropriate scales for field mapping and publications
Order 1 —Very intensive (e.g., experimental plots, individual building sites, required reviews and permits from regulatory agencies)	The soils in each delineation are identified by transecting or traversing or even grid mapping. Soil boundaries are observed throughout their length. Remotely sensed data are used as an aid in boundary delineation.	1 or less	Phases of soil series; misc. areas	Mostly consociations; some complexes; misc. areas	1:15,840 or larger
Order 2 —Intensive (e.g., general agriculture, urban planning)	The soils in each delineation are identified by field observations and by remotely sensed data. Boundaries are verified at closely spaced intervals.	0.6 to 4	Phases of soil series; misc. areas; few components named at a level above the series	Consociations, complexes; few associations and undifferentiated groups	1:12,000 to 1:31,680
Order 3 —Extensive (e.g., range, community planning)	Soil boundaries are plotted by observation and interpretation of remotely sensed data. They are verified by traversing representative areas and by some transects.	1.6 to 16	Phases of soil series or taxa above the series; misc. areas	Mostly associations or complexes; some consociations and undifferentiated groups	1:20,000 to 1:63,360

Table 4-4.—continued

Order and level of data needed	Field procedures	Min. size of map units *(ha)*[1]	Typical components of map units	Kind of map units[2]	Appropriate scales for field mapping and publications
Order 4 —Extensive (e.g., general soil information for broad statements concerning land use potential and general land management)	Soil boundaries are plotted by interpretation of remotely sensed data. They are verified by traversing representative areas and by some transects.	16 to 252	Phases of soil series or taxa above the series; misc. areas	Mostly associations; some complexes, consociations, and undifferentiated groups	1:63,360 to 1:250,000
Order 5 —Very extensive (e.g., regional planning, selection of areas for more intensive study)	The soil patterns and composition of map units are determined by mapping representative ideas and like areas by interpretation of remotely sensed data. Soils are verified by some onsite investigation or by traversing.	252 to 4,000	Phases of levels above the series; misc. areas	Associations; some consociations and undifferentiated groups	1:250,000 to 1:1,000,000 or smaller

1 This is about the smallest delineation allowable for readable soil maps. In practice, the minimum size of delineations is generally larger than that shown in table.

2 Where applicable, all kinds of map units (consociations, complexes, associations, and undifferentiated groups) can be used in any order of soil survey.

Order 1 Surveys

Order 1 (or first order) surveys are made if very detailed information about soils, generally in small areas, is needed for very intensive land uses. These land uses commonly require reviews and permits from regulatory agencies, engineers, and other professionals. Order 1 surveys are also conducted for specialized information, such as for critical habitat or cultural resources. The information can be used to plan for irrigation, drainage, truck crops, citrus or other specialty crops, and experimental plots; to site individual building lots; to locate disturbed areas or anthropogenic landforms (see chapter 11); to delineate wetlands and special habitat; and for other uses that require a detailed and very precise knowledge of the soils and their variability. Order 1 surveys are also referred to as high-intensity soil surveys.

Transecting, traversing, and, in some cases, grid mapping are used for accurate placement of soil boundary lines over small distances. Soil boundaries can be marked in the field with flagging for accurate location by GPS or standard land surveying methods and later transferred to a base map using mapping software. Remotely sensed data and digital techniques using LiDAR and ground-penetrating radar (chapter 6) can aid in soil boundary delineation. Typically, soil pits are used to determine parent material, bedrock, and drainage classes. They are mechanically dug with small excavators or backhoes.

Order 1 surveys have high map unit purity. Map units are typically consociations, containing no more than 15 percent dissimilar minor components. Complexes are seldom used. Map unit components can be phases of soil series, taxonomic categories above the soil series, or miscellaneous areas. Some map units may be named at a categorical level above the series or named for the type of material (e.g., "excavated," "regraded"). Soil mapping legends may use taxonomic categories or connotative terms that are customized for users. Delineation size is designed to meet the detailed needs of the survey. Many order 1 surveys use a minimum size of about 1 hectare (2.5 acres). Depending on scale, environmental concerns, and needs of the survey, as small as 2,000 square feet may be used. Base map scale is generally 1:15,840 or larger and may be as large as 1 cm = 15 m (1 inch = 20 feet). Order 1 base maps may also have perimeter surveys determined by a professional land surveyor and show detailed topography with less than 2-foot interval contour lines. Order 1 surveys may employ significantly different methodologies than traditional order 2 and 3 surveys, such as a connotative legend. A connotative legend has map unit symbols that notate specific interpretive or inherent properties of the taxonomic component (e.g., drainage class, texture, hydrologic soil group) or any aspect of a component that is of interest to the user. Typical end users of a high-intensity soil survey, such as engineers, regulatory agency staff (Federal, State, and local), land developers, wetland scientists, site evaluators (e.g., septic system designers), and other professionals, generally are not familiar with the named soil series on a map.

Due to the deviations from normal soil survey standards to accommodate unique user needs and the lack of a formal soil correlation process, order 1 surveys in the U.S. are treated as special types of onsite investigations and are not part of the official soil survey for the National Cooperative Soil Survey. Order 1 surveys can differ from order 2 and 3 surveys in the landscape models used to explain soil and landform distribution. It is useful to view order 1 components at an order 2 or 3 level to better understand landscape patterns.

Order 2 Surveys

Order 2 (or second order) surveys are made if detailed information about soil resources is needed to make predictions of soil suitability and treatment needs for intensive land uses. The information can be used in planning for general agriculture, construction, urban development, and similar uses that require precise knowledge of the soils and their variability.

Field procedures allow plotting of soil boundaries by observation and by interpretation of remotely sensed data. The soils in each delineation are identified primarily by traversing and transecting. Observations and remotely sensed data are secondary types of documentation. Boundaries are verified at closely spaced intervals. Map units are mostly consociations and complexes but may also include undifferentiated groups or associations. Map unit components are phases of soil series or phases of miscellaneous areas. Map units may also be named for a taxonomic category above the series. Delineations are variable in size, with a minimum of 0.6 hectare to 4 hectares (1.5 to 10 acres), depending on landscape complexity and survey objectives. Contrasting minor components vary in size and amount within the limits permitted by the kind of map unit used. Base map scale is generally 1:12,000 to 1:31,680, depending on the complexity of the soil pattern within the area.

Order 3 Surveys

Order 3 (or third order) surveys are made where land uses do not require precise knowledge of small areas or detailed soil information. The survey areas are commonly dominated by a single land use and have few subordinate uses. The soil information can be used in planning for range, forest, and recreational areas and in community planning.

Field procedures allow plotting of most soil boundaries by observation and by interpretation of remotely sensed data. Boundaries are verified primarily by field observations, transecting, and remotely sensed data. Secondary types of documentation include traversing representative areas and applying the information to like areas. Map units include associations, complexes, consociations, and undifferentiated groups. Components of map units are phases of soil series, taxa above the series, or miscellaneous areas. Delineations have a minimum size of about 1.6 to 16 hectares (4 to 40 acres), depending on the survey objectives and complexity of the landscapes. Contrasting minor components vary in size and amount within the limits permitted by the kind of map unit used. Base map scale is generally 1:20,000 to 1:63,360, depending on the complexity of the soil pattern and intended use of the maps.

Order 4 Surveys

Order 4 (or fourth order) surveys are made if general soil information is needed about the potential and general management of land for extensive uses. The information can be used in locating, comparing, and selecting suitable areas for major kinds of land use, in regional land use planning, and in selecting areas for more intensive study and investigation.

Field procedures permit plotting of soil boundaries primarily by interpretation of remotely sensed data and transecting. Secondary documentation types are field observations. Traverses are made in representative areas to determine soil patterns, and the information is applied to like areas. Transects are made in selected delineations to estimate map unit composition. Most map units are associations, but some surveys have consociations and undifferentiated groups. Map unit components are phases of soil series, taxa above the series, or miscellaneous areas. Minimum size of delineations is about 16 to 252 hectares (40 to 640 acres). Contrasting minor components vary in size and amount within the limits permitted by the kind of map unit used. Base map scale is generally 1:63,360 to 1:250,000.

Order 5 Surveys

Order 5 (or fifth order) surveys are made to collect soil information in very large areas at a level of detail suitable for planning regional land use and interpreting information at a high level of generalization. The primary use of this information is selection of areas for more intensive study.

Field procedures consist of mapping representative areas 39 to 65 square kilometers (15 to 25 square miles) in size to determine soil patterns and composition of map units. This information is then applied to like areas by interpretation of remotely sensed data. Soils are identified by a few onsite observations or by traversing. Map units are typically associations but may include some consociations and undifferentiated groups. Map unit components are phases of taxa above the series level and miscellaneous areas. Minimum size of delineations is about 252 to 4,000 hectares (640 to 10,000 acres). Contrasting minor components vary in size and amount within the limits permitted by the kind of map unit used. Base map scale ranges from about 1:250,000 to 1:1,000,000 or smaller.

Two Orders of Soil Survey in the Same Project

Some soil survey areas have two or more separate and distinct parts with different needs. For example, one part may be mapped to make predictions related to irrigation and the other may be mapped to make predictions related to range management. For the irrigated part, areas are mapped at the intensity required for an order 2 soil survey and map unit components are mostly consociations of narrowly defined phases of soil series. For the rangeland part, areas are mapped as an order 3 survey and map units are associations, complexes, and some consociations of more broadly defined phases of soil series or of taxa above the series. Some map units of the two parts will consist of the same kinds of soil, but it is essential that map units for the two different orders of soil survey maps do not have the same names or symbols.

Large, separate, and distinct areas that are within the same project but are surveyed by different methods need to be distinguished clearly by boundaries on the published soil map or on a small-scale inset map. Each part should be identified by a note printed parallel to the line separating the areas of each survey order. The two parts need separate legends. The parts are considered as distinctly different orders of soil survey, but the results are reported in the same publication. The same or different map scales may be used for the different survey orders, depending on the intended uses.

Many order 2 surveys delineate some map units by methods that are less intensive, even though the areas mapped at different intensities are intermingled on the map. For example, within an otherwise detailed soil map, the delineations of very steep or very stony soils are commonly investigated at the intensity normally used for an order 3 survey.

Other soil surveys include areas consisting of two or more distinctive soils that could be mapped separately by detailed soil survey methods but are not, because the cost of making the separation cannot be justified. For example, a survey area that is mostly productive soils suitable for general farming may contain large areas of unproductive sandy soils covered with thick brush. Although the sandy areas contain contrasting kinds of soil that could be delineated separately, the cost of detailed mapping to separate the kinds of soils may outweigh the expected benefit. The outer boundaries of the sandy areas are plotted in as much detail and with as careful investigation as any other boundaries of the soil survey, but the sandy areas themselves are mapped using order 3 or order 4 methods. Traverses are made, and the composition of the areas is defined in terms of the kinds, proportions, and patterns of the individual soils. The delineations are described in the text of the published soil survey as soil associations mapped by methods of the appropriate survey order.

It is important to note that many soil survey areas in the U.S. were recompiled from their original mapping and publication base scale during soil survey digitizing in the 1990s. Surveys containing intensively managed or populated areas and also vast remote areas or wild lands were mapped using multiple map scales that were recompiled and digitized as a single base layer at a scale of 1:24,000. Original mapping and publication scales can be determined by referencing the original printed maps and correlation data.

Correlation Steps

Soil correlation is a multi-step quality assessment process (fig. 4-6) that ensures accuracy and consistency both within and between soil surveys on both local and regional bases. It involves classifying soils, naming map units, and providing accurate interpretations. The purpose of correlation is to provide consistency in designing and naming map units, provide effective transfer of information to and between users, and allow flexibility between the standards used in soil survey and the variability scientists observe and document geographically. Correlation is a continuous process, from the initial descriptions at the start of mapping through the final manuscript, tables, map development, and certification. It is the responsibility of all survey team members, and the decisions are based primarily on the standards used to create the survey (see table 4-5).

The correlation process is an integral part of soil survey. It is carried out on a continuing basis throughout the course of the project. Soil correlation can be described by the following steps: (1) design of map units, (2) characterization of map unts, (3) classification of map unit components, (4) correlation of map units, and (5) certification.

Figure 4-6

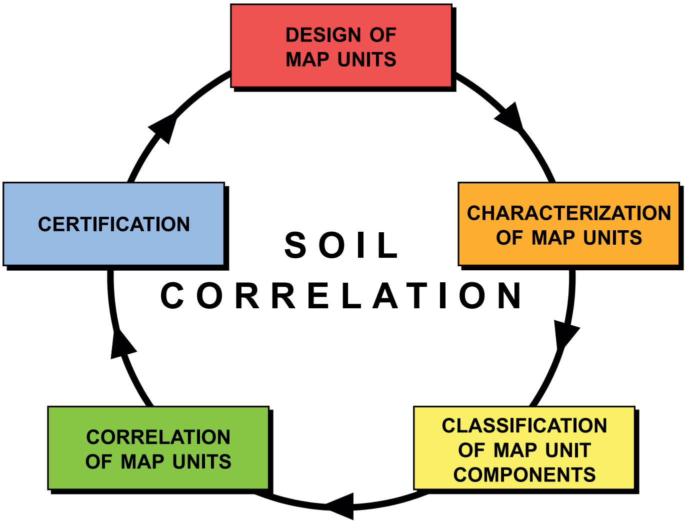


Diagram that illustrates soil correlation is a continuous process, not a single event. The process is used to facilitate consistent collection, identification, grouping, and transfer of soil information.

Design of Map Units

Every soil survey must begin with a clear understanding of the purpose and needs for the project. At a minimum, a project plan must be developed to outline the needs of a soil survey. Preferably, all partners in a survey create a memorandum of understanding and agree to it. These documents outline the scale to be used in making the survey, minimum delineation size for map units, kinds of map units, documentation requirements, and interpretation needs of the soil survey users. Commonly, there is agreement on soil-landscape models to be used and the important soil-forming factors and soil orders known in a project area. These documents are essential to balancing survey detail, survey costs, and time frames for a project.

A map unit can be tentatively correlated as soon as it has been accurately described and mapped. Map units in a survey are correlated to ensure consistency in design and level or order of mapping in a survey area.

Characterization of Map Units

Map unit characterization includes identifying the kind of components (see table 4-1 in the "Soil Map Units" section) and the kind of map units to use and what data to collect for the soil database. Surveys in high-value, heavily used areas may require that most map units be consociations with components identified to the series level. Surveys in remote areas used primarily for watershed protection or wildlife habitat may only require that map units be complexes and associations with components named for taxonomic categories above the series.

Classification of Map Unit Components

Soil pedons representing the components of the map unit are described and classified to the appropriate taxonomic level (series or higher). In addition to pedon description and classification, laboratory characterization data are collected, and interpretive features (such as ecological site descriptions; see appendix 4) may be developed. The importance of this information cannot be overemphasized. The descriptions and data provide the basic information needed for complete and accurate interpretation. Working from the soil descriptions, supervisory soil scientists can give maximum help to the survey team.

Soil taxa (series or higher category) are used to name the components making up the map unit. Soil map unit components are correlated internally to ensure that classification is consistent and that the recorded properties coincide with established taxonomic limits. Property ranges documented for the component that extend slightly beyond the taxonomic ranges are used to document and interpret the map unit component. Laboratory data supports the aggregation or grouping of pedons as well as soil database population. Pedons described in U.S. surveys use the Soil Taxonomy system of classification.

There are four main purposes of Soil Taxonomy. The first is to facilitate communication among soil scientists. Soil Taxonomy allows scientists to group and sort thousands of soil series in a meaningful way. Groupings can be made at various map scales by using different levels of the classification hierarchy. For the most detailed surveys, soils are grouped into the series level of components. Some order 4 surveys may use families or phases of higher taxa. Small-scale surveys may use the order or suborder level in Soil Taxonomy.

The second purpose of Soil Taxonomy is to provide names for taxa that are based on formative elements. For example, soil orders (such as Aridisols) begin with a formative element and end in “sol,” the Latin word for soil. The taxa names quickly convey information about soil, including diagnostic horizons and features, moisture and temperature regimes, and natural fertility. Use of the formative elements helps organize knowledge about soils.

The third purpose is to provide a link between the conceptual classes in Soil Taxonomy and actual natural bodies of soils. The conceptual classes embody current understanding of soil genesis and geographic distribution of soils worldwide. Through the correlation process, the specific natural soil bodies (components) making up the map units depicted in soil survey maps are assigned names using the taxonomic system.

Lastly, Soil Taxonomy provides a way to transfer information and technology. It allows the transfer of information about soil properties and performance gathered at one location to other locations where the same soil occurs.

Correlation of Map Units

The correlation of map units impacts many subparts of a soil survey. Similar and dissimilar soils should be consistently and objectively evaluated and listed in map unit descriptions and databases to properly account for the complexity in a survey. A system of analyzing this information should be developed and followed. Analysis methods might include the use of spatial analysis software or tabular information in databases to identify correct groupings.

Taxonomic unit descriptions represent the range in characteristics of the dominant soils in a survey area. Each map unit should reference a typical pedon that describes the range of characteristics for that taxa within the survey. The typical pedon, and commonly the taxonomic unit description, represent only a portion of the full range in characteristics for a given soil series.

Soil interpretations and ratings are correlated to ensure that soil suitabilities or limitations are evaluated equitably across the survey. Correlation ensures consistency within the map unit descriptions, including consistent wording to describe important features and consistent use of performance data among map units having the same use and management.

Map unit correlation also includes the proper documentation of the map unit history. This includes conceptual changes that may occur over the course of a survey project as new areas are identified for use of the same map unit. Current surveys maintain and track this history in a soil database.

Certification

Soil surveys typically have a formal, final correlation document that summarizes all correlation decisions within a survey project. This document lists the final versions of map unit and taxonomic legends and explains the reasons for combining soils into map units, any classification anomalies, and any geographical exceptions. An explanation of the correlation of map units and components between adjoining survey areas ensures consistency between surveys. Both initial and update surveys use a similar process to explain correlation decisions and to present new information and data collected to support those decisions.

Correlation documents certify that a soil survey product has followed and met the standards used to make a survey. This certification is essential for product delivery. Current delivery of U.S. soil surveys uses the publicly available Web Soil Survey (Soil Survey Staff, 2016b).

Quality Control and Quality Assurance

Quality control and quality assurance provide consistency in a survey, for mapping, classifying, and naming soils. They also include joining maps, database population, and developing interpretations. Survey activities that ensure consistency include field visits, field reviews, and survey team communication. Quality control is the process of evaluating, prioritizing, and coordinating survey activities to ensure that products meet the agreed-upon standards and user needs. It is carried out on a daily basis by each member of the soil survey team. It requires that each member be aware of the standards used in making the soil survey and adhere to those standards in their daily activities. Quality assurance is a review and assessment process, commonly led by senior soil scientists and carried out on a periodic basis. This process provides review of completed work and training of staff members to support and ensure soil survey quality for users. Progressive reviews of completed work are performed to discover and correct errors or inconsistencies within the survey and ensure consistent use of standards throughout a soil survey project. Problems identified during reviews are corrected and can be used to provide training to the survey team.

It is essential that everyone involved in making a soil survey has a thorough understanding of the standards used to conduct it. Table 4-5 lists ways standards are used in creating soil surveys. Standards are dynamic, changing to meet current needs of users and keep pace with technology. It is important to know what the standards were when a soil survey was initially made because they will impact soil survey maintenance and update.

Table 4-5

Major Applications of Soil Survey Standards

- Designing and controlling map legends
- Identifying, describing, and classifying soils in the field
- Delineating soil boundaries on a map
- Determining map unit composition
- Populating soil databases
- Preparing map unit descriptions
- Selecting and classifying representative pedons
- Naming map units
- Conducting special studies
- Preparing or testing interpretations
- Preparing soil survey manuscript and database
- Preparing correlation documentation
- Making documentation requirements
- Evaluating data
- Developing analytical procedures

Records and Documentation

Keeping definitions and names of soil taxa up to date is essential for identification of map units, for correlation of soils nationwide, and for transfer of information about soils at one place to similar kinds of soil elsewhere. Different methods can be used and periodically modified. Some kind of centralized system is needed to obtain a nationwide perspective, to maintain standards for defining soil taxa, to assemble field and laboratory data, and to disseminate information to the field. See chapter 7 for more information.

Soil Series Definitions

Soil series are used for naming most map units in U.S. soil surveys. There are currently more than 22,000 series defined and named. Soil series definitions are the framework within which most of the detailed information about U.S. soils is identified with soils at specific places. They also provide the principal medium through which detailed information about the soil and its behavior at one place is projected to similar soils at other places. The concepts of the series category and of individual series have changed over time.

Rigorous standards for definitions of soil series ensure that names and descriptions for the same kinds of soils are consistent from survey to survey. Consistency is a major objective of the correlation process. The classes of the soil series category are not static. As new knowledge is acquired, definitions of some established series must be modified. New series are defined for newly recognized kinds of soils. Changes in criteria or limits of taxa in higher categories commonly require modification of definitions of member series.

Keeping records of series names and updating definitions of series is a continuous process. Changes should be made in ways that detract the least from the predictive value associated with the earlier definitions and names. A centralized system for keeping records of soil series names and definitions ensures that names and definitions of soil series meet the rigorous standards needed in a national soil survey program.

Official Soil Series Descriptions

Each soil series must be defined as fully and accurately as existing knowledge permits. This applies to proposed soil series used in an individual survey as well as to established series. To ensure the inclusion of essential information and to permit comparison of series definitions, a standard format for recording specific kinds of information is used.

Official soil series descriptions (OSD) record definitions and other relevant information about each series. The format and the kind and amount of detail may change from time to time, but a detailed definition is essential. Generally, descriptive information is also needed to aid the reader in identifying the soil in the landscape and relating it to other kinds of soil.

Since soil series are not listed and described in *Soil Taxonomy*, a system is required to record and store this information in an easily accessible format. In the United States, soil series are maintained in the Official Soil Series Descriptions database (Soil Survey Staff, 2016a). An official soil series description in the U.S. includes the features and sections listed below, in the order shown. Some items (such as 1, 2, 4, 16, and 17) are partly or wholly applicable only in the U.S. system designed to store series descriptions. This list can be modified for other systems. See appendix 1 for an example of an official soil series description.

Features and sections of an OSD:

1. Location line with first instance of series name and the States using it (FIPS code)

2. Status of soil series (tentative, established, or inactive)
3. Initials of authors (up to three sets of initials; those of the original author are listed first)
4. Date of latest revision in mm/yyyy format (auto-generated if using the SC-OSD maintenance tool)
5. Name of soil series
6. Introductory paragraph. It includes information on the general nature of the soil (including soil depth, drainage, and parent material and its probable sources); landscape information (including position on landform and slope ranges); and climatic information (such as average annual air temperature, annual precipitation, frost-free season, and elevation). It may also include specific information important to the pedogenic processes and landscape evolution for the series.
7. Taxonomic class. The full taxonomic name of the family taxon is given. It indicates the classes that provide limits of properties that are diagnostic for the series at all categorical levels, except for those between series of the same family.
8. Typical pedon. A typical pedon and its horizons are described in as much detail as necessary to recognize taxonomic class. Horizons and features that are diagnostic for the pedon are described.
9. Type location. The location at which the pedon was described is specified. It is given in geographic unit coordinates and is descriptively accurate enough that it can be identified in the field.
10. Range in characteristics. The ranges of properties of the series are described. This section also contains statements about the relationship of the series control section and diagnostic horizons to vertical subdivisions of the typical pedon.
11. Competing series. The series is distinguished from the other series within the same or similar class with which it might be confused. Competing series commonly share limits with the series described or are members of the same family.
12. Geographic setting. The physiography and landscape in which the soil occurs are described.
13. Geographically associated soils. Other soils with which the series is closely associated geographically are identified.
14. Drainage and saturated hydraulic conductivity ("permeability" in older series). Drainage of the soil is described by drainage class or other means of description relative to soil moisture regimes and the rate of water movement through the soil. Seasonal wetness or dryness, if important, is also described.

15. Use and vegetation. Major uses of the soil and dominant kinds of vegetation that grow on it are described. Native plants, if known, are identified.
16. Distribution and extent. The known geographic distribution (generally physiographic areas, States, and MLRAs) is given along with whether the soil occupies a small, intermediate, or large aggregate area.
17. Soil survey regional office (SSRO) responsible. This is the NRCS soil survey regional office that provides quality assurance review and maintenance of soil series records.
18. Series proposed or series established. Date and location of the soil survey project in which the series was established are given.
19. Remarks on diagnostic horizons and features recognized in the pedon. All of the diagnostic horizons and features, including thickness, depth, and horizons needed in determining the taxonomic class, are listed.
20. Additional data as needed. This section is generally used to document sampling and laboratory analysis associated with the series and information specific to the survey or investigation project.

Other items that may enhance the official soil series descriptions for a broader audience include:

- Pictures of the profile and landscape setting for individual series, and
- Ability to search archived series descriptions for diagnostic features, horizon thicknesses, and other soil characteristics that need to be interpreted.

Soil Handbook

The descriptive legend is the main document governing field operations, but it is only part of the information compiled during a survey. The descriptive legend—the basic document of a soil survey—consists of four parts: (1) description and classification of the soils, (2) identification legend, (3) conventional and special symbols legend, and (4) general soil map and legend. The descriptive legend and the other information about the soils in the survey area are organized into a soil handbook (not to be confused with the *National Soil Survey Handbook,* which is the repository of NCSS policy and guidance). The soil handbook is used by the field team and by engineers, agronomists, planners, and others who need information about the soils of the area before the survey is completed.

The soil handbook contains everything needed for the published soil survey, plus material that is important to the soil scientists making the survey. A detailed outline for the text of the published soil survey should guide development of the handbook. The descriptive legend and soil handbook should follow the same format that will be used for the published soil survey. A soil handbook that is kept up to date as mapping progresses will require a minimum amount of editing after the mapping has been completed.

In addition to the mapping legend, a soil handbook includes interpretations and general sections covering topics related to the kinds of soil in the area, such as climate, physiography, relief, drainage, geology, and vegetation. This information improves the understanding of the properties, distribution, use, and management of the soils.

A record of the extent of each map unit is also maintained. In some surveys, the map unit extent is recorded progressively as the field sheets are completed. In other surveys, progressive extent records of each map unit are kept only until the unit is deemed extensive enough to keep in the legend. The final tally is made after the survey has been completed.

Some items prepared for the mapping legend or handbook may be incorporated into different sections of the publication. For example, the genetic key and classification table could become part of the section on how the soils formed and how they are classified. Some diagrams could be used in that section as well as in the section on the general soil map.

Description and Classification of the Soils

The descriptive legend includes descriptions of the soil taxa as they occur in the survey area and descriptions of map units delineated on field sheets. These descriptions form the primary reference document for identifying kinds of soils and miscellaneous areas and provide the information needed for proper classification, correlation, and interpretation. They also provide the information needed to recognize the map units in the survey area. Descriptions of the taxa and the map units, including the ranges in characteristics within the survey area, ensure that all members of the field team classify and map the soils consistently. Creating a clear, concise, accurate, and complete set of descriptions of the soils is a difficult and important job.

An up-to-date record of what has been learned about the soils is especially important when members of a survey team change. If the project leader leaves before completion of the survey area, an up-to-date descriptive legend of how the soils have been classified and mapped ensures continuity in survey operations.

The project leader organizes the information that has been gathered about the soils in an area. While preparing the descriptions, the project leader may discover items that need clarification or supporting field data. Field studies can then be planned to clarify concepts and improve knowledge of the soils.

Guidelines for describing soils presented earlier in this chapter emphasize individual pedons and polypedons used to define soil map unit components. The soil descriptions in the descriptive legend give the properties of pedons and polypedons plus the extent of the components in each map unit, the variations in properties and in extent of components from one delineation to another throughout the survey area, and the geographic relationships of components within each map unit and of map units to each other. Compete descriptions of the soils in the survey are made from detailed field descriptions of pedons and polypedons, laboratory data, brief notes about internal properties and surface features, and summaries of transects. Appendix 2 gives an example of a map unit description.

As the descriptions of the soils are prepared, each map unit description is compared with the standard definition of the soil for which it is named and with the descriptions of closely related soils. The classification of the soils must be consistent with the descriptions of the components in the map units and also with the standard definition of series or other taxa.

A table of classification is included in the descriptive legend and shows how soils in the survey area fit into the national system of soil classification as presented in *Soil Taxonomy*. If soil series are used in naming map unit components, the table can list the series alphabetically, followed by the classification. Otherwise, the soils can be arranged according to the appropriate families, subgroups, etc.

The nature, kind, position, and amount of minor components are also described for every map unit. The extent, position, and significant differentiating characteristics of soils that are dissimilar to the named components of the map unit are particularly important. The extent and nature of minor components that have interpretative or management characteristics similar to those of the major components should also be determined.

Written descriptive records of the soils are references for an ongoing soil survey. The properties of a soil commonly vary from one part of a survey area to another and may be evaluated differently as a result of increased experience in the area. The soil descriptions are continually revised and updated as mapping progresses. During mapping, new map units and taxonomic units are commonly added and units determined to be of limited extent are discontinued.

As mapping progresses, kinds of soils that do not fit any map units in the legend commonly are discovered. If the kind of soil is extensive and uniquely different from the soils in other map units, it is added to the legend after it has been defined by a project member and approved by supervisory soil scientists of the cooperating agencies. Some new kinds of soil can be treated by redefinition of existing map units, and others can be treated as minor components. New, approved map units must be promptly listed in the legend and defined so that all members of the project team can use them correctly.

Some soils are so limited in extent that they should be included in other map units. It may be best to combine two or more soils that have similar use and management in one map unit. Soils that are so closely intermingled that they cannot be delineated separately should be mapped as complexes. Deletions and other changes are not made formally until the supervisory soil scientists have reviewed the proposed legend changes and deemed them acceptable. If proposed changes are not acceptable, the agency representatives and the project leader resolve any issues. A complete record is kept concerning changes in map units and the disposition of any discontinued map unit. Any changes made between field reviews are recorded in the report of the next field review.

Distinctions between map units must be larger than the ranges that normally occur in measuring diagnostic properties and locating soil boundaries. The soil descriptions must be tested to ensure that the map units are recognized and delineated consistently.

Progressive mapping by the field team is a continuing test of the legend. Inadequacies are evaluated, and any necessary changes are made in the legend. Changes are recorded on all copies of the legend, and each soil scientist in the team must clearly understand the new concepts.

Field notes are summarized periodically, and the summary is recorded in the revisions of the soil descriptive legend. If observations are not summarized and recorded promptly, they may be lost or not used by other members of the survey project.

Field reviews also test the legend and its use in mapping to determine whether survey objectives and requirements are being met. Such reviews typically involve supervisory soil scientists and representatives of cooperating agencies.

Identification Legend

A symbol is placed in each delineation on the map for identification. The identification legend is a list of these symbols and the names of the map units they represent. In some legends, the names of the map units are listed alphabetically, followed by their symbols. This list of names is used by soil scientists as they map. In other legends, the symbols are listed numerically or alphabetically, followed by their names. This list is used by everyone who reads the maps. Typically, both lists are prepared.

The identification legend links names of map units to delineations on the soil maps through the map unit symbols. Many conventions and systems are used for selecting symbols. The choice of symbols is unimportant provided that the symbols are short, that each symbol is unique, and that the map unit that each symbol represents is named and described.

All symbols must be legible on the maps when viewed on a computer screen or in hard-copy printouts. Long symbols are problematic. If they are made small enough to place on the map they may be illegible. They commonly must be placed outside small delineations and arrowed to them. This increases the chance of error. Experience and tests have shown that map users have difficulty reading field sheets that have many symbols placed outside the areas to which they correspond. If the symbol is arrowed from a large delineation to a small one, many users assume that it represents the large delineation. In addition, potentially confusing combinations in symbols should be avoided. They include the lowercase letter l with the number 1 and the capital letter O with the number 0 (zero). While map unit symbols consisting of numbers are simplest to manage, care is needed to ensure that they are distinguished from other numbers, such as coordinates, grid numbers, and other numeric attribution that may appear on finished maps.

The map symbols are primarily used to identify map units delineated within the polygons. Annotation using soil map symbols connotative with a particular soil or property should be avoided. Connotative symbols typically result in a legend that fails to achieve its primary purpose. Any connotative value of symbols may be offset by decreased legibility of the map. Use of connotative map symbols can lead to confusion and mistaken association of map symbols to soil component names, especially when map legends from adjoining survey areas are viewed together. Map users must not assume that connotative symbols or even the map unit names describe all of the important soil properties. The set of soil descriptions (map unit and taxon descriptions) is essential to the purpose of the soil survey and should be used by mappers and by those who need the information while the survey is in progress.

Using the same or similar symbols during the mapping process and on published maps accelerates map compilation because it reduces the amount of time compilers spend converting one set of symbols to another. It also reduces the amount of errors. It is most practical in areas where soils are well known. It is less practical if soils are not well known at the start of the survey, because symbols can change during mapping and correlation.

Taxonomic Legend

Taxonomic legends list all soil component names appearing in map unit names for a survey area followed by their full taxonomic classification. The names of series that are proposed are typically followed by "(P)." The names of series used for a soil taxadjunct are followed by "(T)." The taxonomic classification as observed and described in the survey area is used for the taxadjuncts.

Conventional and Special Symbols Legend

Conventional symbols on soil maps show many natural and cultural features other than map units and their boundaries. They help users locate delineations. Special symbols identify some areas of soils or miscellaneous areas that are too small to be delineated at the scale of mapping. All symbols must be defined. Definitions of special symbols should specify the size of area that each represents.

General Soil Map and Legend

The general soil map helps the field team in mapping and organizing fieldwork. It also provides, for any user of the soil survey, a general overview and introduction to the major soils and their pattern of occurrence in the survey area. The draft of the general soil map prepared during preliminary field studies is refined as more is learned about the soils. The properties, distribution, and extent of the soils in each general area and their suitabilities, limitations, and potentials are described. Significant differences in soil moisture or soil temperature between areas can also be shown on the general soil map.

Soil Maps Made by Other Methods

Although most soil maps published in the U.S. by the National Cooperative Soil Survey are made from field investigations, some are compiled from other sources. These kinds of soil maps are described below.

Generalized Soil Maps

Some users need soil information about areas larger than individual fields or tracts, perhaps as large as several square kilometers. A detailed map tends to obscure the broad relationships. Generalized soil maps are made to reveal geographic relationships that cannot be seen readily on detailed maps. Most soil survey reports include a general soil map for the area. The scale of these maps depends on the intended uses.

Generalized soil maps are made by combining the delineations of existing soil survey maps to form broader map units. A detailed map is generalized by enclosing those larger areas within which a few kinds of soil predominate in relatively consistent proportions and patterns. On the generalized soil map, detailed map units are commonly grouped based on repeating landscape segments and broader physiographic areas. The larger areas are described in terms of the dominant soils. The map is interpreted to show the combined effects of the constituent soils of each map unit.

Generalized soil maps are commonly used to appraise the basic soil resources of whole counties, to guide commercial interests, and to assist farm advisors. They serve as a basis for targeting and implementing agricultural and conservation programs. These maps are increasingly becoming the base maps for county and regional land use planning and for predicting the general suitability of large areas of soils for residential, recreational, wildlife, and other nonfarm uses.

The Digital General Soil Map of the United States (STATSGO2) is the nationally coordinated State-level general soil map of the U.S. It is produced at a scale of 1:250,000 for most of the U.S. and its territories and at a scale of 1:1,000,000 for Alaska. The level of mapping is designed for broad planning and management uses covering State, regional, and multi-State areas. STATSGO2 is comprised of general soil map units and is maintained and distributed as a spatial and tabular dataset.

Schematic Maps

Schematic maps (also called reconnaissance maps) differ from generalized soil maps in being compiled from information other than pre-existing soil maps. Scale is commonly 1:1,000,000 or smaller, although maps made at larger scales can be useful in some cases. Schematic soil maps are commonly made as a preliminary step in locating areas where further investigation is justified. For many areas, especially in undeveloped regions, a schematic soil map is useful in advance of an organized field survey. Some maps serve as the only source of soil information in areas where more intensive studies are not feasible.

Schematic soil maps are made by using many sources of information to predict the geographic distribution of different kinds of soil. Information about climate, vegetation, geology, landforms, and other factors related to soil are gathered and studied. Data obtained by remote sensing techniques, including aerial photography and satellite multispectral band imagery, may be useful. Any available information about the soil is used to the extent justified by its quality. Some soil information is available for most parts of the world, but the information for remote areas may be mainly notes by travelers and rough maps interpreted from aerial photographs and never verified on the ground.

Thematic Maps

Thematic maps are created by combining delineations of soil maps based upon a singular property theme, including soil features (e.g., surface texture, depth to water table, or salinity). They commonly represent interpretative qualities, such as suitability for septic tank absorption fields, land capability classification for farming, or hazards to use (such as flooding). Thematic maps provide a geographic comparison of a singular soil quality or feature across broad land areas. The use of digital soil map products and GIS systems together with soil attribute databases enables rapid creation and manipulation of thematic soil maps that can be easily understood by land managers and policy makers.

GIS technologies and digital mapping techniques (see chapter 5) are extremely valuable in developing generalized, schematic, and thematic maps. Combining digital data drawn from other sources with known soil information can increase the precision of map line placement as well as improve the purity of the composition or consistency in identification of soil components.

Supporting Data

Data collected during the course of a soil survey is recorded and analyzed, and then integrated in mapping, interpretation, and correlation decisions. The most notable types of supporting data and information developed are transects, field notes, photographs, laboratory analyses, investigations, special interpretations, climatic data, geology maps, vegetation maps, and research reports.

Notes are indispensable parts of the mapping legend. Some notes are used in revising the descriptive legend, which becomes incorporated into the manuscript for publication. Notes help make mapping faster and more accurate. They may record tonal patterns on aerial photographs that are peculiar to a certain map unit, the relationship between minor but key indicator plants, or surface configurations that have little bearing on use or management but help the mapper locate significant soil areas. Notes and other information needed in mapping, but not intended for publication, can be kept on separate sheets after each taxon or map unit description in the descriptive legend.

Photographs of soil profiles can be very effective in illustrating some soil features. Photographs or diagrams of soil systems and landscapes show the relationships of soils to various landscapes. Cross-sectional and three-dimensional diagrams of parts of the survey area are also helpful.

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CHAPTER 5

Digital Soil Mapping

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Principles and Concepts

Digital soil mapping is the generation of geographically referenced soil databases based on quantitative relationships between spatially explicit environmental data and measurements made in the field and laboratory (McBratney et al., 2003). The digital soil map is a raster composed of two-dimensional cells (pixels) organized into a grid in which each pixel has a specific geographic location and contains soil data. Digital soil maps illustrate the spatial distribution of soil classes or properties and can document the uncertainty of the soil prediction. Digital soil mapping can be used to create initial soil survey maps, refine or update existing soil surveys, generate specific soil interpretations, and assess risk (Carré et al., 2007). It can facilitate the rapid inventory, re-inventory, and project-based management of lands in a changing environment.[1]

SCORPAN Model

The scientific foundation of soil mapping is Hans Jenny's (1941) conceptual model that soils (S) on a landscape are a function of five environmental factors, namely climate (cl), organisms (o), relief (r), parent material (p), and time (t):

$$S = f(cl, o, r, p, t)$$

While this model, sometimes known as CLORPT, has been useful in conventional soil mapping, it is not quantitative nor spatially explicit.

1 Trade or company names used in this chapter are for informational purposes only. This use does not constitute an endorsement by USDA–NRCS or the contributing authors of this chapter.

To represent soil and the related environmental factors in a spatial context and express these relationships quantitatively, McBratney et al. (2003) proposed the SCORPAN model, where soil (as either soil classes, S_c, or soil attributes, S_a) at a point in space and time is an empirical quantitative function of seven environmental covariates: soil (s), climate (c), organisms (o), relief (r), parent material (p), age (a), and spatial location (n):

$$S_{c,a} = f(s, c, o, r, p, a, n)$$

The important advances of the SCORPAN model for use in digital soil mapping are: (1) the recognition that the environmental factors are not necessarily independent of each other and are thus defined as environmental covariates, (2) the inclusion of soil as an environmental covariate, (3) the spatially explicit nature of the model, and (4) the quantitative nature of the functional relationships. In the SCORPAN model, soil, either as point observational data, existing soil maps, or remotely sensed spectral properties, can be used as input data. Environmental covariates are digital and spatially explicit data in a raster that is processed using a geographic information system (GIS). The SCORPAN model facilitates the quantification of the relationships between spatially explicit digital environmental covariates and the soil classes or attributes to be predicted in a spatial context. It also facilitates the estimation of error or uncertainty of the spatial prediction of soil classes or properties.

Digital vs. Conventional Soil Mapping

The availability and accessibility of geographic information systems (GIS), global positioning systems (GPS), remotely sensed spectral data, topographic data derived from digital elevation models (DEMs), predictive or inference models, and software for data analysis have greatly advanced the science and art of soil survey. Conventional soil mapping now incorporates point observations in the field that are geo-referenced with GPS and digital elevation models visualized in a GIS. However, the important distinction between digital soil mapping and conventional soil mapping is that digital soil mapping uses quantitative inference models to generate predictions of soil classes or soil properties in a geographic database (raster). Models based on data mining, statistical analysis, and machine learning organize vast amounts of geospatial data into meaningful clusters for recognizing spatial patterns.

Various digital soil mapping tools, methodologies, and inference models have been developed and tested in the U.S. and abroad to facilitate the rapid visualization and quantification of landscape patterns at multiple spatial scales (Lagacherie et al., 2007; Hartemink et al., 2008; Behrens et al., 2010; Minasny et al., 2012). A significant amount of the data used in digital soil mapping can be archived in a spatially explicit digital format in a GIS, so the expert knowledge used to predict soil distribution on the landscape is retained. Objective sampling plans can be implemented to statistically capture variability of the landscape, representing it by digital environmental covariates. Probably the most exciting aspect of digital soil mapping is the ability to generate spatially distributed information on soil classes and/or properties and the associated estimate of uncertainty (the probability that a particular soil type and/or property occurs at a specific point on the Earth's surface). There is a great demand globally for spatially distributed soil information. This is evidenced by the launch of GlobalSoilMap (Arrouyas et al., 2014), a project to make a digital soil map of the world using state-of-the-art technologies for soil mapping and predicting soil properties at 100-m resolution.

Maps that predict the spatial distribution of soil classes or properties are of interest in many countries because they inform soil use and management decisions. Digital soil mapping better captures observed spatial variability and reduces the need to aggregate soil types based on a set mapping scale (Zhu et al., 2001). An important component of digital soil mapping is the method of analysis used to define the relationship between soil observations and environmental covariates. Many types of methods have been investigated, including expert systems (Cole and Boettinger, 2007; Saunders and Boettinger, 2007; Zhu et al., 2001), unsupervised classification (Boruvka et al., 2008; Triantifilis et al., 2012), and machine learning or predictive modeling (Behrens et al. 2005; Behrens and Scholten, 2006; Bui and Moran, 2003; Stum et al., 2010; Brungard et al., 2015).

Discrete vs. Continuous Models

Discrete Models

A map of soil classes, such as soil map units, is a type of discrete, or crisp, model (Hole and Campbell, 1985; Burrough and McDonnell, 1998). Discrete models represent thematic or categorical data in which the values represent a predefined class with a finite number of possibilities. These models are typically nominal, ordinal, or binary and therefore lack numerical meaning. When applied in a raster, each pixel value represents the class associated with the pixel (e.g., soil class A, soil class B, soil class C, etc.). Mathematical operations cannot be applied directly to discrete data because the values do not have true numerical meaning (e.g., soil class B is not twice as great as soil class A).

Soil mapping has traditionally used the discrete model to represent distinct soil types and groups of soil types on the landscape. In a raster environment, discrete models simplify the display of modeled classes and align conceptually with the conventional soil survey approach. However, discrete soil class models present the assumption that soils are constant across a class. Classes can be defined either narrowly or broadly for any soil landscape unit, similarly to how the traditional map unit can be categorized as a consociation or complex. Narrowly defined classes are best for providing site-specific interpretations and are most suitable in situations where sufficient field observations (training data) are available to adequately define the classes. Broadly defined soil classes may help bridge the gap from conventional (polygon, vector) to digital (raster) soil mapping and are most suitable in situations where field observations (training data) are limited.

Continuous Models

A map of soil properties is a type of continuous model. Continuous models represent data in which the values are measurements or calculations that have numerical meaning and represent a continuum. In a raster environment, each pixel value represents a real quantitative value (measured, calculated, or inferred) and can have various levels of precision (e.g., integer or floating point). Continuous models allow for any value over a continuous range, whereas discrete models have only a finite number of predefined outcomes.

Continuous soil models are designed to handle the continuous nature of soil properties more realistically than discrete models. In theory, continuous models eliminate the disadvantages of predefined classes and distinct boundaries in soil mapping. In practice, the continuity depends upon the cell size and the precision used. Predictions of soil properties are typically represented with a continuous data model.

The majority of the environmental covariates used in digital soil mapping are continuous data models. Terrain attributes derived from a digital elevation model (DEM), such as slope gradient, curvature, and area solar radiation, are continuous models. Spectral data, such as reflectance, derived from satellite or aircraft remote-sensing platforms are also continuous models.

Stages and Processes

Typically, each digital soil mapping project is unique. Many aspects of a project may vary (e.g., the objectives of the project, the biophysical properties of the study area, the availability of environmental covariates, the method of prediction applied). However, the stages and processes of digital soil mapping should be consistent in all projects. Each stage comprises a series of specific objectives that must be accomplished for the digital soil mapping project to progress. The digital soil mapping process is iterative and requires review and assessment at several points. The stages and processes of digital soil mapping projects are outlined in the following list and described in the following subsections.

Outline of Stages and Processes

Stage:

1. **Define area and project scope**
   a. Define and refine objective: soil classes or properties
2. **Identify physical features of interest**
   a. SCORPAN—important covariates and appropriate data
   b. Scale of processes and measurements
   c. Available measurements (field and remote sensing)
3. **Data sources and preprocessing**
   a. Identify and acquire data
   b. Assess data quality
   c. Organize data
   d. Preprocess data
4. **Data exploration and landform analysis**
   a. Derive terrain and spectral data products
   b. Select appropriate predictors
5. **Sample for training data**
   a. Case-based and *a priori* samples
   b. Field samples

   Review and assess:
   - Do the data layers represent the important environmental covariates?
     - o Yes—proceed to Stage 6
     - o No—return to Stages 2, 3, and 4
   - Are the training data adequate to predict the classes or properties of interest?
     - o Yes—proceed to Stage 6
     - o No—return to Stage 5

6. **Predict soil classes or properties**
    a. Choose and apply appropriate prediction method
        i. Soil classes – unsupervised or supervised classification, predictive modeling
        ii. Soil properties – predictive modeling, geostatistics

    Review and assess:
    - Are the prediction results reasonable?
        - Yes—proceed to Stage 7
        - No—apply a different prediction method, combination of predictors, or set of training data—return to Stages 4, 5, and 6
7. **Calculate accuracy and uncertainty of results**

    Review and assess:
    - Are accuracy and uncertainty results acceptable?
        - Yes—proceed to Stage 8
        - No—revisit prediction method, predictors, and training data—return to Stages 4, 5 and 6
8. **Apply digital soil mapping**
    a. Produce soil class or property maps
    b. Evaluate existing maps
    c. Create soil information products
    d. Apply to other disciplines

Defining the Area and Scope of the Project

Before beginning a digital soil mapping project, it is important to clearly define the project area and scope. For example:

- What is the specific objective of the project?
- Is the project intended to create initial soil survey information or to update existing soil mapping and data?
- Is the objective to produce a map for a specific purpose?
- What is the geographic extent of the project area?
- What are the biophysical characteristics of the area?
- How are the biophysical characteristics of the area related to the distribution of soils on the landscape?
- At what spatial scale is the expected variation in soil distribution expressed (local vs. regional)?
- Are soil classes and/or soil properties to be predicted?
- What is the scale of the final map product(s)?

Digital soil mapping can address a variety of questions. The key is to determine how digital soil mapping can be applied in *your* project area to achieve *your* objectives.

Identifying the Physical Features of Interest

Environmental Covariates and Appropriate Data

The first step after defining the area and scope is to determine which environmental covariates are most important to soil development and distribution in the project area. Once these are determined, the related specific terrain and spectral characteristics can be identified and appropriate digital data selected to allow the discrimination of those physical phenomena. Five environmental covariates in the SCORPAN model are commonly derived from digital data: soil properties (s), organisms (o), parent material (p), relief (r), and climate (c). How humans have altered the Earth's surface may also be considered, which in some cases can represent the time or age (a) covariate.

Soil (s).—Soil can be represented by covariates derived from: (1) georeferenced point data representing field and/or laboratory measurements, (2) remotely sensed spectral data, or (3) existing soil maps. Digital data may include point data such as soil taxonomic class, soil depth to bedrock, or soil chemical or physical properties by genetic horizon (e.g., soil laboratory data associated with a georeferenced sample location at the NRCS Kellogg Soil Survey Laboratory). Surface or near surface properties of the soil may have diagnostic spectral signatures distinguishable by remote sensing data. For example, Nield et al. (2007) used Landsat 7 ETM+ data to digitally map the occurrence of soils with surficial accumulations of gypsum, which was distinguished by a normalized difference ratio of the two shortwave-infrared (SWIR) bands (bands 5 and 7). Existing soil class data in the form of soil maps may also be useful, particularly in soil survey update projects or in disaggregating soil map unit associations into soil components (Nauman and Thompson, 2014).

Organisms (o).—Organisms are typically represented by vegetation or land cover digital data, including existing land cover data and remotely sensed spectral data. Existing land cover data can include maps of vegetation, land use, and species distribution, such as those available from the National Gap Analysis Program (USDI-USGS, 1999). Vegetation is commonly represented by remotely sensed spectral data because green vegetation reflects near infrared (NIR) and absorbs red electromagnetic radiation. The Normalized Difference Vegetation Index (NDVI) is a normalized difference band ratio of the NIR and red bands of a multispectral image. The values range from -1.0 to 1.0—higher values indicate higher vegetation density. NDVI can be quantified for any spectral data source that contains NIR and red bands, such as Landsat data. For example, NDVI was an important covariate in digitally mapping the occurrence of badlands with very low vegetation cover in the Powder River Basin in Wyoming (Cole and Boettinger, 2007).

Parent material (p).—Parent material can be derived from a geology map or gamma radiometric data or by using remotely sensed spectral data to discriminate mineralogical correlates of parent material. Mineral assemblages in different parent materials (rocks and sediments) will vary in spectral response. Mineralogy is particularly responsive in the SWIR range of the electromagnetic spectrum, represented by Landsat TM or ETM bands 5 and 7, Landsat 8 OLI bands 6 and 7, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) bands 4 through 9. For example, the San Francisco Mountains in the Great Basin of southwestern Utah are characterized by mixed sedimentary rocks (mainly quartzite) intruded by igneous rocks (mainly andesite) with mixed basin fill. A principal components analysis of Landsat ETM+ bands 1 through 5 and 7 helped distinguish an andesite intrusion from sedimentary rocks and showed the influence of andesite on the composition of the alluvium downslope from the intrusion (Stum et al., 2010).

Relief (r).—The covariate representing relief can be derived from elevation data, such as Light Detection and Ranging (LiDAR), the National Elevation Dataset (NED), Interferometric Synthetic Aperture Radar (IFSAR), photogrammetric data, etc. These data derivatives are known as terrain attributes or elevation derivatives. Examples of terrain derivatives are slope gradient, slope length, slope curvature, wetness index, ruggedness index, slope aspect, landform, and relative elevation. Various combinations of terrain attributes can generate geomorphic surfaces and describe processes related to soil development.

Climate (c).—The climate covariate can be approximated in some areas by elevation, especially in landscapes subject to orographic effects (i.e., higher elevations are subject to cooler temperatures and greater amounts of precipitation). Regional climate models and data are also available, e.g., climate data at about 800-m resolution in the U.S. from the PRISM Climate Group (2016). Solar radiation is commonly an excellent proxy for climate, particularly in aspect-driven climate scenarios. Solar radiation models are widely available and can be calculated in various GIS software packages.

Age (a).—While not commonly considered a SCORPAN covariate, soil age has a major impact on the degree of profile development and soil properties. Humans, for example, play an important role in altering the landscape and/or land cover, thus changing soil properties (attributes), soil classes, and land use. Therefore, in some cases the human impact on the landscape can represent age. One example is the northern part of the Las Vegas area, Nevada, where humans have urbanized the arid desert landscape and created green space via irrigation. In many areas, petrocalcic horizons have been destroyed, changing the habitat necessary for rare endemic plant species, and irrigation has altered soil properties and regional hydrology by leaching salts out of soils, raising water tables, and disrupting natural waterflow patterns. Human alterations of the landscape and land cover may also indicate soil properties. For example, the parts of a landscape converted into agriculture may indicate the location of soils that have desirable properties, such as lower contents of rock fragments or lower levels of salinity.

Scale of Processes and Measurements

The processes responsible for the development and distribution of soils on the landscape operate over a wide range of spatial scales, from continental (e.g., tectonic events and glaciation) to regional (e.g., deposition of alluvium and windblown sand) to hillslope (erosion and deposition) to pedon (addition, removal, transformation, and translocation of materials). These processes, their interactions, and their scale of spatial expression can create complex soil patterns. The processes must be understood and represented by the appropriate measurements for both environmental covariates and field observations. Digital data can be used to stratify landscapes into relatively homogenous geological and geomorphic units, which are helpful in understanding these processes and developing an appropriate design for collecting data in the field.

Field measurements.—Field measurements in digital soil mapping are derived from georeferenced points. They may be full or abbreviated pedon descriptions and associated laboratory data. The goal is to predict soil classes and properties beyond the location of field observations. Soil sample size and the area or volume of representation should be considered when determining the location of field sampling sites and timing of measurements (Bouma et al., 1989; Mohanty and Mousli, 2000).

Remote sensing measurements.—Remote sensing has been defined as the "art and science of deriving information from measurements made at a distance" (Colwell, 1997). Remote sensing measurements detect electromagnetic radiation from the Earth's surface in two different ways: passive and active. Passive remote sensing collects electromagnetic information produced as a result of the interaction between the sun's energy and surface materials, such as measurements collected by satellite sensors. Active remote sensing collects information returned from the Earth's surface as a result of an emitted signal, such as LiDAR (Light Detection and Ranging) or radar. (See chapter 6 for more information on remote sensing and other tools for proximal soil sensing.)

Remote sensing measurements that provide digital elevation and spectral response data are commonly used in digital soil mapping. The remote sensing of topography via passive sensors (e.g., aerial photographs) or active sensors (e.g., LiDAR) results in the generation of digital elevation models. The use of digital elevation models in soil mapping is extensive and well documented because variations in relief are closely linked to the distribution of soil properties and classes. Remote sensing of spectral data provides direct information about the surface properties of soils, vegetation, or other materials. Spectral properties remotely sensed at the surface can be related to environmental covariates that control soil development. The spectral properties can therefore potentially be used to infer other soil characteristics. Specifically, remote sensing data can be used to map the variations in relief, climate, organisms, parent material, and even time (indirectly).

When reviewing remotely sensed data sources, the data collection mechanism, the extent and consistency of the data, and the scale of the data compared to the scale of the physical phenomena need to be considered. The spatial detail, the spectral wavelengths of imagery, and even the season of the year or other temporal aspects of the physical environment that influence the timing of data acquisition should also be considered.

Because remote sensing measurements are collected at varying spatial and spectral resolutions, careful consideration should be given to selecting data at the appropriate spatial and spectral scale to represent the environmental covariates and processes in the project area. The focus should be the specific scope of a project, e.g., what spatial and spectral resolution is most appropriate for the question(s) being asked? These needs should then be compared against the range of data that is actually available given budget or other constraints.

Selecting Data Sources and Preprocessing

Identify and Acquire Data

One of the most critical steps in a digital soil mapping project is selection of the data. Incorporating data that match the question or problem being considered is essential to the success of the project. The properties of the data should be directly related to the physical attributes and soil-forming processes in the area of interest. For example, in mountainous areas a 30-m DEM might adequately characterize the significant features on the landscape. In low-relief areas where soil formation is driven by very subtle changes in topography, a much higher resolution DEM may be necessary to adequately characterize the terrain features. Several studies have shown that soil-landscape relationships exist over a range of scales (Thompson et al., 2001; Smith et al., 2006; Park et al., 2009). Spatial information commonly has to be down-scaled or up-scaled to match other environmental covariates.

A project may require a mix of data to adequately represent the multiple SCORPAN covariates that influence soil development in a particular area. Elevation derivatives and spectral derivatives are a powerful combination for predicting soil classes or properties in most areas. However, depending on the question being considered and the physical features of the area, a project may require only one of these data sources.

In the United States, there are multiple sources for both DEMs and remote sensing images. One of the largest archives of remote sensing imagery is the USGS EarthExplorer site (USDI-USGS, 2016a). The USGS National Elevation Dataset provides DEMs for most locations (USDI-USGS, 2016b). Many States have archives available for DEMs (USGS and LiDAR), Landsat, and ASTER imagery and should be investigated as potential data sources. The NRCS Geospatial Data Gateway also provides many different types of data layers (USDA-NRCS, 2016a).

Assess Data Quality

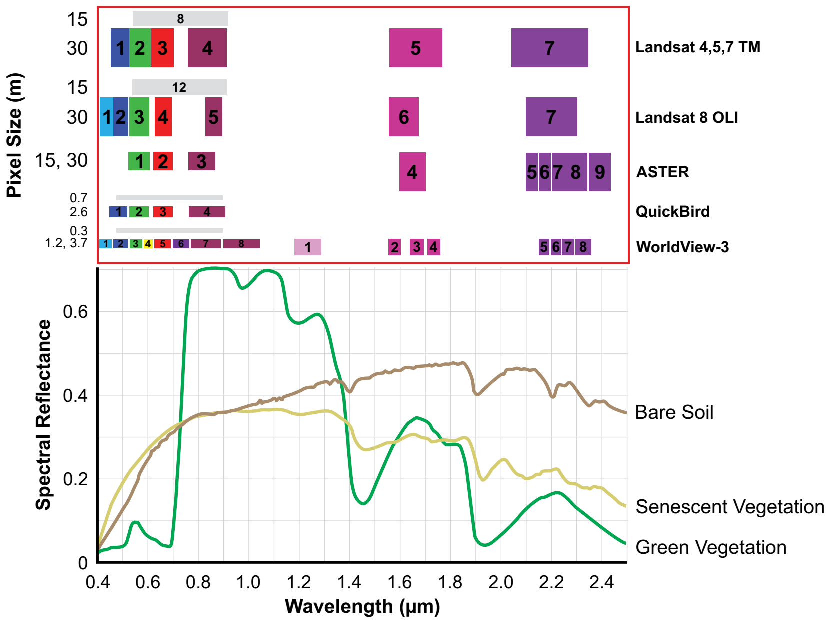
Once data sources have been identified, the quality of the data should be assessed to ensure the best data available are being used for model development. Data attributes to be considered include resolution, spatial projection, units, and source.

Resolution.—Resolution of the data is one of the most important attributes to consider when selecting data. Many high-resolution data sources are currently available, but they may not address the problem being considered. High-resolution data can provide "too much information" and add undesirable noise and/or excess data storage and processing time to analysis and modeling. The scale of physical features or properties on the landscape should be considered when choosing the most appropriate resolution.

The types of resolution—spatial, spectral, temporal, and radiometric—must be considered. Spatial resolution applies to all data sources and equates to grid cell size. In deciding the appropriate spatial resolution, the features of interest on the landscape must be considered; the grid cell size must be able to adequately capture the desired features. One rule of thumb is that the smallest object recognized should be equivalent to four grid cells of a DEM (Rossiter, 2003).

When considering spectral data derived from remote sensing sources, spectral resolution may be the most important attribute. Spectral resolution refers to the number of bands of data a sensor provides and which part of the electromagnetic spectrum they capture. Generally, the red and NIR part of the spectrum is most important if the focus is vegetation and the SWIR part of the spectrum is most important if the focus is minerals, parent materials, or bare soils (fig. 5-1).

Figure 5-1



Comparison of spectral bands of common sensors to the reflectance spectra of common materials.

Temporal resolution indicates the time of year and frequency of image acquisition. Seasonality or repetition of image acquisition over several years may be an important variable. In addition, noting the date of acquisition is important if several images are mosaicked together. Ideally, the images for a mosaic should be acquired on or near the same date to minimize differences in atmospheric and Earth surface conditions. If data meeting those criteria are not available, and data from different years are used, the data used should at least be from the same time of year. Image acquisition frequency typically ranges from every day (e.g., MODIS and AVHRR) to every 16 days (e.g., Landsat).

Radiometric resolution is an important, though rarely considered, spectral sensor attribute. It refers to the number of gray levels the sensor can potentially differentiate. Gray levels describe the brightness values (BV) or the digital number (DN) values that are recorded for an image. Because these quantization values are integers, they are only whole numbers. Therefore, there is a direct correlation between the range of numbers that are used in describing an image and the level of detail in the brightness variation.

Spatial projection.—It is important to ensure that all digital data are the same spatial projection (geographic vs. projected datum, etc.) for ease of processing. There are many software packages that can be used to define the projection (if data comes without a projection file but the projection is known) and re-project the data. The georeferencing of the data should be checked by comparing key features in a data source with the same key features in a reliable image source, such as the National Agriculture Imagery Program (NAIP). If georeferencing needs to be corrected, many software packages offer this functionality.

Units and data type.—Understanding the units of the data and how to interpret them is important. If units between data sources are not compatible (e.g., feet vs. meters for a DEM), values may need to be converted. Data ranges should be noted as they will impact certain classification methods.

The data type and how the data are stored should also be noted, such as whether the data is a floating point (contains decimal places) or an integer and the number of bits of the data. For integers, 1-bit data are binary and store 2 values (0 and 1), 8-bit data can store 256 values, and 16-bit data can store 65,536 values. Floating point numbers are either single (32 bit) or double (64 bit). Another aspect to consider is the file type: thematic (discrete, categorical) or continuous. Typically, thematic data are integer and continuous data are floating point. The numbers in a continuous dataset have intrinsic meaning and represent real physical measurements (elevation or reflectance) or are the result of a calculation that has been performed on the data (e.g., wetness index from elevation, spectral band ratio from reflectance). In contrast, thematic (categorical) data typically represent an interpreted class. All of the information needed to properly understand the data typically can be found in the file's metadata.

Data issues.—Several issues may occur with data, but most can be resolved during preprocessing. For spectral imagery, issues include clouds, smoke, sun glint, data loss, and calibration. When possible, another image of better quality should be used. Images without clouds and smoke are preferable since these issues cannot be resolved through preprocessing. If an alternate image is not available, data preprocessing techniques should be tried to reduce the impact of sun glint, data loss, or calibration issues on analysis.

Elevation data are developed to model the bare earth terrain features from a number of sources, and each source has a unique set of issues. The most frequently used form of elevation data in digital soil mapping is a raster surface comprised of a matrix of cells arranged in rows and columns. The elevation values in the cells can be interpolated from points or contour lines. The accuracy of the elevation values themselves is commonly reported for data sources and indicated in the metadata. Accuracy typically is expressed using root mean squared error (RMSE) as related to the absolute error of the elevation surface. Smaller RMSE values more closely match the absolute elevations of the modeled surface. The spatial resolution of a cell determines the level of characterization detail that can be attained for the analysis of the bare earth terrain features. The cell size used should not exceed the accuracy level of the source data.

DEMs derived from hypsography (digital contour data), also called HypsoDEMs, will have a characteristic contour-line bias, which is expressed as an artificial, terraced landscape. DEMs produced from hypsography may also have flat-topped ridges, peaks, and indistinct junctures between footslopes and toeslopes. The contour line interval is a critical factor when considering the use of DEM-derived data for terrain analysis, especially in areas of low relief. Derivative products created from the HypsoDEM in which the contour line interval exceeds the change in relief will portray features that reflect the locations of the contour lines and not the features of the terrain surface. No satisfactory solutions are available to correct this problem.

DEMs produced from LiDAR may have areas of uncertainty associated with vegetation and the presence of water. Areas with dense vegetation may have few to no returns of the emitted signal from the actual ground surface. The LiDAR sensor rarely receives a return when the pulse makes contact with any surface water. Areas with very shallow water will have either no data collected or will have points where the pulse contacted vegetation above the water surface. In these cases, the DEM will have elevations that are greater than the actual ground surface. If there are isolated patches of dense vegetation, artificial "spikes" may occur in the DEM. In areas with mixed land cover, such as cultivated cropland and small woodlands, the effect of the wooded areas may be pronounced. Performing a minimum focal filter in association with iterative focal smoothing operations can help minimize these problems.

DEMs produced from radar (such as x-band radar, e.g., IFSAR) will not represent the bare earth surface where vegetation is present unless augmented with elevation data from another source. Unlike LiDAR, IFSAR produced with x-band radar will not adequately penetrate vegetation to model the bare earth surface. In addition, IFSAR is not sensitive to features with abrupt changes in slope, such as narrow, convex ridges or concave, closed depressions. Because DEMs from this data source may mute the expression of such features, modifications should be made to accurately reflect terrain derivatives such as slope or curvature, or the less defined representation of the features should be acknowledged.

Artifacts derived from the data management scheme used in the source data may be apparent with DEMs developed from LiDAR or radar data. Tiling is an effective method of managing and processing the large volumes of source data. It organizes the data into small, systematic, rectangular grids. The juncture between adjacent tiles may introduce inadvertent artifacts. One or several smoothing (Gaussian or focal) operations may be able to adequately blend away these artifacts. However, the best practice is to consult the original data source (if available).

Organize Data

A data management plan is needed at the onset of a project. It should include a common directory structure, file naming convention, minimum metadata standard or other means of documentation, and a data backup process. This plan is particularly important if the project will include multiple members of a team accessing and utilizing the same data. It should be simple enough for the members to effortlessly implement.

One approach is to keep the original data sources separate from the processed data. The folder structure should represent the steps in the process, and the names of folders and files should reflect their content. The processing and analysis steps and the file naming convention should be kept in a separate document or in the metadata. Regardless of the folder structure and naming conventions, the processing steps of the project could be used as a guide to organizing the data.

Preprocess Data

Data rarely are in an immediately usable format. Some degree of preprocessing typically is needed before the data can be incorporated into analysis or modeling. Some basic guidelines for data preprocessing are:

- Ensure that all data are in the same projection and have the same extent.
    - Select natural boundaries when possible for the project area and include a buffer around the perimeter of the area when clipping or subsetting data for processing. This minimizes or eliminates potential edge-effect from processing along the margins of a dataset.
    - Use a snap raster to maintain consistency in grid cell alignment.
- Validate georeferencing with a reliable image source (e.g., NAIP).
- Normalize spatial resolution (grid cell size) between layers.
    - If multiple datasets are being combined, it may be best if they share a common spatial resolution.
- For elevation data, include in DEM preparation:
    - Filling sinks and trimming peaks;
    - Removing linear, human-made artifacts (e.g., roads, railroads, channelized waterways);
    - Applying a low-pass filter or other smoothing algorithm; and
    - Ensuring that derivatives based on hydrology (e.g., flow accumulation, upslope contributing area, topographic wetness index, stream power index) encompass entire watersheds for consistent interpretation and application of values across the entire project area.
- For spectral data, apply image standardization or atmospheric correction to calculate surface reflectance when:
    - Mosaicking images for classification (if images were not acquired on the same day/time and under the same atmospheric conditions);
    - Calculating band ratios;
    - Extracting biophysical information from the image (biomass, NDVI); and
    - Extending class signatures across multiple images, particularly if images were acquired on a different date or location.

Landsat 4, 5, 7, 8 surface reflectance products are available from USGS EarthExplorer (USDI-USGS, 2016a).

- If a mosaic is required, apply all the preprocessing prior to mosaicking.
- Stratify the area to reduce variability for analysis, modeling, or classification.
    - Choose a stratification that applies to the overall goal of the project and is based on natural boundaries, such as geology, elevation, physiographic areas, etc.

Data Exploration and Landscape/Landform Analyses

The process of digital soil mapping requires exploring the data available for a project and linking it to key SCORPAN covariates and pedological knowledge. With the soil processes and end goal of the project in mind, an exploration analysis should be used to determine if the data will provide adequate information on the variability and distribution of key covariates across the area of interest. Commonly, unexpected variation in the data is discovered and an evaluation is needed to determine if real information or noise is represented. In most cases, the development of terrain or spectral data derivatives is necessary to exploit the data to its full potential for predicting soil classes or properties.

Deriving Terrain Attributes

Terrain attributes are derived from DEMs and are typically represented using the raster data format. Elevation can also be represented as points (e.g., LiDAR returns) or triangulated irregular networks (TIN), but the raster format is typically preferred due to its greater flexibility. Elevation data are typically developed from contours, topographic surveys, or LiDAR data. Terrain attributes may be broadly grouped into two categories: (1) primary attributes, which are computed directly from a DEM; and (2) compound attributes, which are combinations of primary attributes (Moore et al., 1991). The field of geomorphometry (Hengl and Reuter, 2008) has advanced with the technology of GIS and is contributing to the evolving list of terrain attributes. Table 5-1 lists some terrain attributes commonly used in digital soil mapping. An exhaustive list is available in Wilson and Gallant (2000). All these terrain attributes can be calculated using commonly available GIS and statistical software packages (e.g., ArcGIS, SAGA, R).

A critical variable to consider when calculating terrain derivatives is the neighborhood size used. The typical raster GIS operation uses a roving window of 3 x 3 cells when calculating first and second derivatives, such as slope gradient and slope curvatures, respectively. This small window can be problematic if the source DEM has a high resolution (e.g.,

Table 5-1

Selected Primary and Compound Terrain Attributes Used in Digital Soil Mapping

Attribute	Measures	Biophysical property
Primary		
Curvature	Second derivative of slope	Flow characterization, i.e., runoff or run-on
Relief, a.k.a. Topographic Ruggedness (Riley et al., 1999)	ABS(Zmax – Zmin) for specified neighborhood	Broad characterization of terrain (infers parent material)
Normalized Slope Height, a.k.a. Relative Elevation or Relative Position	(Z – Zmin)/(Zmax – Zmin) where Z = elevation of center cell for specified neighborhood	Relative landform position, catenary sequence, vegetation distribution
Compound		
Solar Radiation (Hofierka and Suri, 2002)	Estimates potential or actual incoming solar radiation for specified time interval	Solar energy incidence on surface, a means of modeling aspect
Wetness Index, i.e., Topographic Wetness Index (Moore et al., 1991)	W = (A/S) where A = upslope contributing area for a cell and S = the tangent of slope gradient	Spatial distribution of zones of saturation for runoff (assumes uniform soil transmissivity within the catchment)
Potential Drainage Density (Dobos and Daroussin, 2005)	Cell count of stream segments within specified neighborhood	A measure of landscape dissection
Morphometric Protection Index (Olaya and Conrad, 2009)	A measure of topographic openness	Plant communities, soil development, impact of wind
Multi-Resolution Valley Bottom Flatness Index and Ridge Top Flatness Index (Gallant and Dowling, 2003)	Process to differentiate valley floor and ridgetop positions	Landscape position
Geomorphon (Jasiewicz and Stepinski, 2013)	Landform classification based on line-of-sight	Crisp landform classes, catenary sequence

< 10 meters) or contains substantial noise. For example, calculating a slope gradient from a 3-m resolution NED DEM for an area in the Midwestern United States using the typical 3 x 3 neighborhood yields a noisy surface, whereas a larger neighborhood yields a smoother surface that better represents the slope patterns that govern soil distribution.

The expanding neighborhood size over which the DEM derivatives are calculated allows flexibility in depicting local or regional features. The larger the neighborhood, the greater the emphasis on broad trends and large features. The most suitable neighborhood size for the modeling target(s) under investigation should be determined. Neighborhood sizes should vary according to the terrain attribute being calculated. For example, an attribute like topographic ruggedness is commonly calculated using a larger neighborhood to characterize a regional trend (e.g., geomorphic/physiographic region) but slope gradient is typically modeled as a localized attribute (e.g., hillslope).

Terrain attributes based on hydrology must be calculated using extents that include intact, complete watersheds. Terrain attributes such as upslope contributing area (flow accumulation), wetness index, stream power index, and downslope distance gradient will have consistent, uniform output values when calculated for complete watersheds, and the output values will have the same meaning when compared across different watersheds.

Another factor related to hydrologically based attributes is the manner in which flow direction is determined. One of the first algorithms developed limited flow to one of the eight directions in a 3 x 3 neighborhood. It is known as the deterministic 8 (D8) algorithm (O'Callaghan and Mark, 1984). The D8 algorithm works well if flow paths are confined to areas of concentrated flow and there is only one cell of lower elevation to route flow toward. Problems occur if the flow is diffuse. More recent algorithms, such as the multiple flow direction method (MFD) (Quinn et al., 1991) or the deterministic infinity (Dinf) method (Tarboton, 1997), allocate flow to multiple directions and so render a flow path that better represents the diffuse nature of water flow.

Several terrain attributes listed in table 5-1 or in Wilson and Gallant (2000) are appropriate for stratifying study areas or defining broad, regional areas. They include Topographic Ruggedness (Riley et al., 1999), Roughness by Relief and Aspect (Behrens, 2003), Hammond's Landforms (1954, 1964), Iwahashi and Pike's Topographic Classification (2007), Fuzzy Landform Elements (Schmidt and Hewitt, 2004), and Geomorphons (Jasiewicz and Stepinski, 2013). Since most of these attributes are based on a large neighborhood, they can be used to describe regional characteristics. Creating combinations of these attributes may also be useful. For example, a crisp class (i.e., Geomorphon landform elements) in combination with relative elevation would be useful for investigations of the relationship between upper, mid, and lower backslopes (Libohova et al., 2016).

Spectral Data Derivatives

Spectral data commonly is transformed (not just used as raw spectral bands) in order to emphasize useful spectral signatures. A spectral data derivative is simply the conversion of spectral data, either digital numbers or surface reflectance, into a new composite spectral variable. Typically, these transformations involve some combination of the spectral values in two or more bands. The original bands represent a measure of radiance for a specific spectral band, whereas the derivative transforms the data and typically represents some information useful for subsequent analysis.

Spectral derivatives are useful for several purposes, including: (1) indices of biophysical properties, commonly related to environmental covariates (SCORPAN); (2) data reduction, by concentrating information into a small number of new bands; and (3) suppression of topographically related illumination variation (considered noise, not information). Of these spectral transformations, the conversion of spectral data into indices of biophysical properties is probably the most important for digital soil mapping. The most effective and widely used biophysical indices relate to vegetation abundance, in part because vegetation has such a distinctive spectral reflectance pattern. However, any physical property, including soil mineralogy and moisture, can potentially be the focus of a transformation if the property has a measurable effect on the spectral reflectance that can differentiate it from other surface materials in an image. Three of the most widely used spectral transformations are band ratios, principal components analysis, and the Tasseled Cap (Kauth-Thomas) transformation.

Band ratios.—Ratios of spectral bands can be used to accentuate the differences between reflectance and absorption features (Jensen, 2005). The two kinds of ratios commonly used are simple and normalized. *Simple ratios* simply divide the digital number (DN) or surface reflectance value (%) of one sensor band by another (e.g., band 1 / band 2). *Normalized ratios* divide the difference between two bands by the sum of the two bands. Because ratios are not scene-dependent, ratios from different images potentially can be compared. Table 5-2 lists commonly used band ratios. The information in the ratio image must be validated with *a priori* knowledge of the area or other measured data. Specialized ratios can be developed based on a surface feature that reflects highly in one band and absorbs greatly in another, such as gypsum (Nield et al., 2007). Ratios must be calculated on atmospherically corrected or standardized images (images converted to surface reflectance).

Table 5-2

Spectral Band Ratios Used in Digital Soil Mapping*

Ratio name	Equation	Sensor/bands	Biophysical property
NDVI[1] (Normalized Difference Vegetation Index)	$\frac{NIR-Red}{NIR+Red}$ Values range from -1 to 1	Red and Near Infrared bands; Landsat 5, 7—bands 3, 4; Landsat 8—bands 4, 5	Healthy green vegetation
Soil Enhancement Ratios[2]	1) Red/Green: carbonates 2) Red/SWIR(a): iron 3) SWIR(a)/SWIR(b): hydroxyls (clay)	See band combinations for carbonate, iron, hydroxyls (clay) ratios below	Three simple ratios for carbonate, iron, and hydroxyls (clay) are combined into one three-layer image
Carbonate Normalized Ratio[3]	$\frac{Red-Green}{Red+Green}$ Values range from -1 to 1	Red and Green bands; Landsat 5, 7—bands 3, 2; Landsat 8—bands 4, 3	Calcium carbonate-bearing minerals
Iron Normalized Ratio[4]	$\frac{Red-SWIR(a)}{Red+SWIR(b)}$ Values range from -1 to 1	Red and SWIR bands; Landsat 5, 7—bands 3, 7; Landsat 8—bands 4, 7	Iron-bearing minerals
Clay (hydroxyls) Normalized Ratio[5]	$\frac{SWIR(a)-SWIR(b)}{SWIR(a)+SWIR(b)}$ Values range from -1 to 1	SWIR bands; Landsat 5, 7—bands 5, 7; Landsat 8—bands 6, 7	Clay or hydroxyl-bearing minerals
Rock Outcrop Normalized Ratio[6]	$\frac{SWIR(a)-Green}{SWIR(b)+Green}$ Values range from -1 to 1	SWIR and Green; Landsat 5, 7—bands 5, 2; Landsat 8—bands 6, 3	Sedimentary (bright pixels) vs. igneous (dark pixels) parent material
Ferrous Normalized Ratio	$\frac{SWIR(a)-NIR}{SWIR(a)+NIR}$ Values range from -1 to 1	SWIR bands; Landsat 5, 7—bands 5, 4; Landsat 8—bands 6, 5	Ferrous iron-bearing minerals

* For documentation and ERDAS Imagine models available for most ratios listed, see USDA-NRCS (2016b).

[1] Jensen, 2005

[2] Developed by U.S. Bureau of Land Management

[3] The carbonate band from the Soil Enhancement Ratio (see above) as a normalized index

[4] The iron band from the Soil Enhancement Ratio (see above) as a normalized index

[5] The clay band from the Soil Enhancement Ratio (see above) as a normalized index

[6] Bodily, 2005; Stum et al., 2010

Principal components analysis.—In applications for remote sensing, principal components analysis (PCA) is an image-dependent data transformation and varies depending on the spectral properties of pixels in the image. Because each PCA transformation is unique, the results of a PCA transformation from one image cannot be compared directly to that from another image. This condition is both a strength and a weakness: a strength because the transformation will adapt to highlight the information present in the particular image, and a weakness because interpreting the results of a PCA transformation can be difficult (i.e., each scene's PCA is different and needs to be interpreted based on its specific transformation).

A PCA transformation is the rotation and translation of the *n* bands of original image data to produce *n* bands of new data, which are orthogonal or mutually perpendicular in spectral feature (n-dimensional) space and uncorrelated. The consequence of this method of arranging the new bands is that most of the variance will be concentrated in a subset of the PC bands (Jensen, 2005). PCA reduces variance of the data in the new PC bands, a reduction which may be desirable. The resulting PC bands should be examined closely to determine which new PC bands contain the most information and could potentially be most useful in subsequent analysis and modeling. The most useful are typically PC 1, 2, 3, but they should be evaluated for each individual image). PCA transformation is available in many software packages and does not require an atmospherically corrected (surface reflectance) image.

Tasseled Cap (Kauth-Thomas) transformation.—The Tasseled Cap transformation is similar to PCA in that it is an orthogonal, multiband transformation. Unlike PCA, the rotations are directed to capture specific biophysical properties and are not scene specific. The original Tasseled Cap transformation was developed for Landsat MSS data and then extended for Landsat TM data. It was based on an analysis of agricultural data from the U.S. Midwest but since has been used globally and for non-agricultural areas (including forestry and urban applications).

The Tasseled Cap transformation is based on the observation that most of the variability in Landsat TM data can be explained by three properties: (1) *brightness*, which is similar to the average DN value across all bands; (2) *greenness*, which is a measure of vegetation abundance, similar to a vegetation index, but which incorporates all the bands and not just red and NIR; and (3) *wetness*, which tends to be correlated with the amount of water present. It is available in image processing software packages, such as ERDAS Imagine, and requires an atmospherically corrected (surface reflectance) image (Jensen, 2005).

Selection of Appropriate Predictors

After data has been explored and appropriate terrain and/or spectral derivatives established, but before the process of model building is started, an optimal set of predictor variables (i.e., covariates) needs to be selected. Digital soil mapping requires spatially exhaustive environmental covariates (SCORPAN) related to the soil class or property of interest. Generating 10s to 100s of covariates is inexpensive and relatively easy (Brungard et al., 2015; Miller et al., 2015; Xiong et al., 2014), particularly when multi-resolution digital elevation models are used (Behrens et al., 2010; Roecker and Thompson, 2010; Smith et al., 2006). Although it is possible to use all available covariates as predictor variables in modeling, it is best to select an optimal subset. Inclusion of non-informative covariates increases model uncertainty, particularly for linear models. Covariate reduction (also known as feature selection) is also important because as the number of covariates increases so does the chance of model overfitting and the amount of computation time. Moreover, simpler models are easier to interpret.

Pedological knowledge should be integrated in the covariate selection process (as described earlier in this chapter) because digital soil mapping is most accurate when fundamentally driven by an expert with significant knowledge of the soil system (Kuhn and Johnson, 2013). If pedological knowledge is lacking or uncertain (particularly regarding scale) and/or if multiple data layers represent the same SCORPAN covariate, these methods should be used. In some cases, semi-automated covariate selection methods can identify a subset of covariates from the larger set of all available covariates so that prediction accuracy is optimized with the fewest number of covariates (Nilsson et al., 2007; Xiong et al., 2014). Pedological knowledge and semi-automated covariate selection methods should be used together (Kempen et al., 2009; Kuhn and Johnson, 2013).

Semi-automated covariate selection methods can be grouped into two broad categories: unsupervised and supervised (Kuhn and Johnson, 2013). Unsupervised methods evaluate covariate relevance outside of a predictive model by selecting covariates that pass some criterion (Kuhn and Johnson, 2013). Supervised methods select optimal covariates by identifying the covariate set that maximizes model predictive ability (Kuhn and Johnson, 2013).

Unsupervised covariate selection methods include correlation analysis, Optimal Index Factor (OIF), and principal components analysis (PCA). Correlation analysis retains or removes covariates that meet a pre-determined correlation threshold. OIF ranks any covariate combinations of three bands so that the within-covariate variance is maximized and the between-covariate correlation is minimized (Kienast-Brown and

Boettinger, 2010; Nield et al., 2007). Combinations with the highest OIF are assumed to contain the most information. PCA transforms covariates so that they fall along the multivariate axes of greatest variance (Fox and Metla, 2005; Levi and Rasmussen, 2014). It eliminates between-covariate correlations, but because it transforms covariates, the results can be difficult to interpret. Unsupervised methods are likely to be most useful when covariates are highly correlated.

Supervised covariate selection methods include forward and backward selection, simulated annealing, genetic algorithms, and the Boruta algorithm. Forward and backward selection iteratively adds (forward selection) covariates or removes (backward selection) covariates to determine which covariates are not significant. Forward and backward selection is particularly useful for linear regression when combined with Akaike's Information Criterion (AIC). Recursive feature elimination is a variant of backward selection that avoids fitting multiple models at each step (Guyon et al., 2002; Kuhn and Johnson, 2013). Simulated annealing modifies an initial random subset of covariates based on a slowly decreasing probability, so that over a number of iterations it becomes very unlikely that a suboptimal covariate set will be selected (Kuhn and Johnson, 2013). Genetic algorithms randomly change multiple covariate sets until a covariate set that produces the most accurate model is identified. The Boruta algorithm scores each covariate against a set of random covariates. Covariates that have importance scores significantly larger than the random covariates are deemed relevant (Kursa and Rudnicki, 2010). Additionally, several tree- and rule-based statistical models (i.e., random forests, cubist models, multivariate adaptive regression splines, and lasso models) conduct intrinsic covariate selection. Because each supervised method has a different approach to covariate selection, different methods identify different optimal covariate sets. Generally, it is useful to compare multiple supervised covariate selection approaches. Implementations of these methods can be found in the caret (Kuhn et al., 2015) and Boruta (Kursa and Rudnicki, 2010) packages for the R software for statistical computing (R Core Team, 2013).

Unsupervised and supervised covariate reduction methods can be used together. For example, in a digital soil mapping study of soil depth in southeastern Utah, correlation analysis was initially used to identify and remove highly correlated covariates from a set of 94 potential covariates. Next, both the Boruta algorithm and simulated annealing were used to identify a final set of 7 covariates. The final covariate set provided equal or better predictive accuracy than larger covariate sets (Brungard, unpublished data).

Qualitative visual inspection of spatial predictions should also be used to assess selected covariates. Covariates which are pedologically and statistically plausible but produce visually incorrect predictions, such as sharp linear boundaries where none exist, should be removed (Padarian et al., 2014).

In summary, optimal covariate selection begins with using existing pedologic knowledge to identify data layers that represent relevant SCORPAN covariates. The result may be a relatively large number of covariates since it is likely that multiple data layers, at multiple scales, can represent each SCORPAN covariate. Supervised and unsupervised techniques can be used to further refine these covariates. The optimal predictor set should be the covariate set that is pedologically and statistically plausible, results in the most accurate model, and produces visually correct predictions. A guide to covariate selection is presented in figure 5-2.

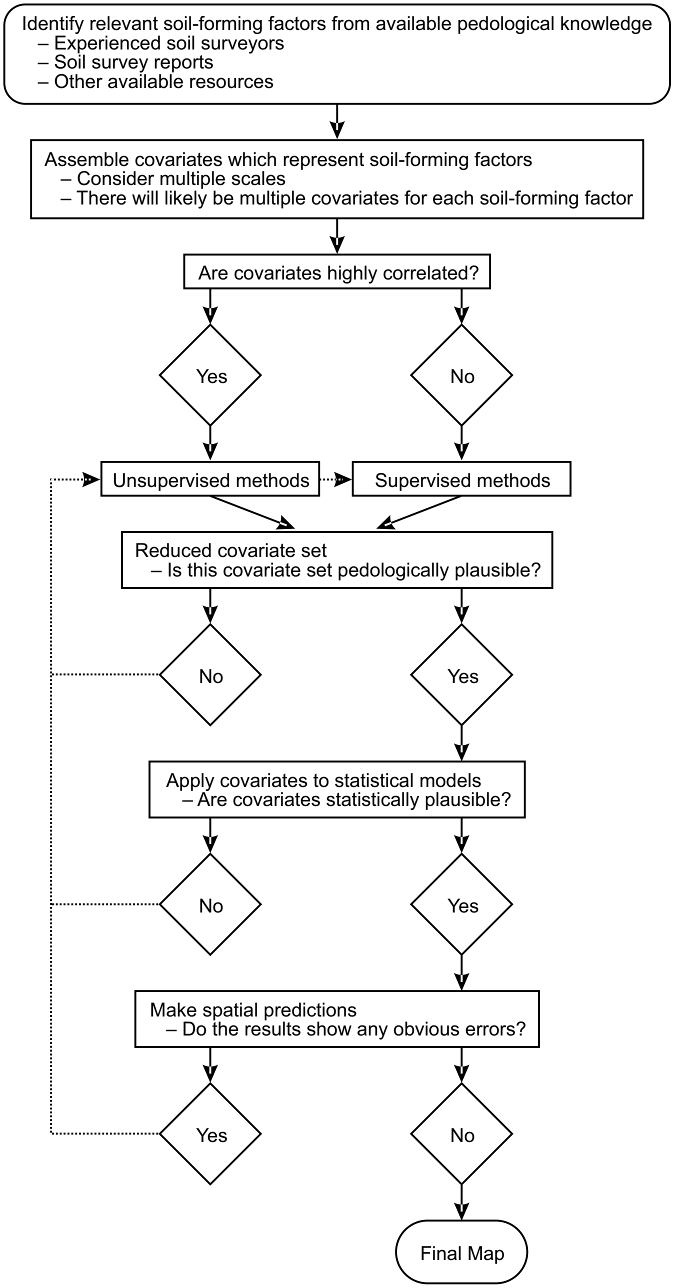
Sampling for Training Data

The digital soil mapping process is dependent on the relationship between predictor variables (i.e., covariates) and the target soil feature (soil class or property) of the model. This relationship applies to both knowledge-driven and data-driven modeling methods. It is important to select samples of covariates that are representative of the distribution of the target soil feature. These samples, known as training data, provide the data that will be used to train the model to predict similar occurrences. Prediction of soil classes or properties is most successful when precise, observed locations of typical soil members are available or when experts can provide precise tacit points. Directed (purposive) field investigations may be used in support of a knowledge-based modeling approach but should not be used exclusively. Random or stratified sampling is more robust and less prone to bias. Training data can be collected with case-based or *a priori* sampling if existing data or knowledge is utilized or by *in situ* sampling if new data are collected specifically for the purpose of training a model.

Case-Based and A Priori *Knowledge Sampling*

Case-based sampling for training data uses prior mapped locations of classes or properties to train a model to map the same classes or properties in unmapped locations. The empirical relationship between the outcome (class or property) and the covariates at known locations (previously mapped) can be used to predict an outcome in unknown areas with similar biophysical characteristics. The known and unknown areas must

Figure 5-2



Flow chart illustrating the general steps in selecting environmental covariates.

have similar soil-landscape relationships. Knowledge of soil-landscape relationships, along with model performance measures (discussed under "Validation and Uncertainty"), should be used to determine how reliable and applicable the empirical relationships will be in unmapped areas.

A priori sampling for training data uses previous knowledge of an area to sample a training data location from the covariate data. It is best applied to classes that are very distinct and whose location is easily determined using high-resolution imagery, such as a rock outcrop or water class. It should not be used for classes that contain more variability, like a soil class, to avoid introducing bias into the sampling process. It is best to use case-based or field sampling for more variable and complex classes.

Field Sampling

Collecting training data in the field is an essential part of the digital soil mapping process. Data must be collected in the field using the selected set of covariates and a sampling design amenable to the modeling objectives. Sample point selection typically is determined using GIS software. Generally, a GPS receiver is used to navigate to sample locations in the field.

The positional accuracy of GPS receivers varies dynamically according to satellite configuration, atmospheric and solar conditions, terrain, and type of GPS receiver in use. If possible, comparable GPS receivers should be used for all data collection activities for a given project. All GPS receivers provide a dynamic display of positional accuracy. A minimally acceptable standard of positional accuracy should be determined for the data collection activities.

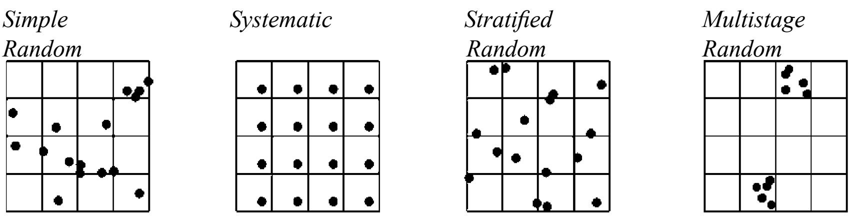
It is important for field personnel to know what the sample is intended to represent. Field computers that display spatial data against the GPS position and sample location are ideal for ensuring that the field location is close to the sample location. In remote areas where computers cannot be used, corroborating information should be supplied to help better reference the site location for field staff. For example, if the sample is located near the juncture of a side slope and footslope, but clearly on the side slope, this information should be given to the field crew. The information should be on a hard-copy field collection sheet or database form. Data collection forms, either digital or hard copy, should be standardized throughout a given project and include all variables needed to satisfy the target modeling objective(s). Including a data field item for GPS accuracy may be helpful and provide a reference throughout the course of a project.

Sampling Design

The choice of sampling design depends on the size and accessibility of the project area, modeling objectives, desired level of confidence and precision, expected variability of the soil feature(s), and the cost of obtaining samples. The selected design needs to satisfy the statistical rigor of randomness as well as remain within the limits of time, money, and staff available for sampling.

Simple random.—Simple random sampling is the most straightforward way to select independent and unbiased samples. Sample locations each have an equally probable chance of being selected (fig. 5-3). This design has the primary advantage of being unbiased and satisfying the statistical requirements of randomness. It gives every location the same probability (i.e., chance) of being selected for sampling. However, this design may result in irregular and/or clustered spacing of samples. In addition, detecting systematic variation may be difficult using this sampling method. This design is most useful for study areas that are small and homogeneous and have few explanatory variables.

Figure 5-3



Simplistic representation of sampling locations as determined by simple random, systematic, stratified random, and multistage random sampling designs.

Systematic.—A sample is taken according to a regularized pattern (fig. 5-3). This approach ensures even spatial coverage. Patterns may be rectilinear, triangular, or hexagonal. This design can be problematic with data that vary cyclically or vary at an interval smaller than the sample spacing. It is important to ensure that selected samples do not coincide with a particular cycle (e.g., the microhighs of hummocks) but fall on the complete spectrum of the population.

Stratified random.—The sampling region is spatially subset into different strata, and random sampling is applied to each strata (fig. 5-3). Strata are typically geographic, such as land cover type, landform, slope gradient, slope aspect, or parent material. It is assumed that these strata are strongly related to the target soil feature(s). Strata may be sampled equally or in proportion to area. However, if the target is rare in the population, it may be preferable to sample the strata equally (Franklin and Miller, 2009; Kuhn and Johnson, 2013). Stratified random sampling offers higher accuracy at lower cost. These benefits are dependent on the suitability of the defined strata, which is dependent on adequate prior knowledge of the target soil feature(s).

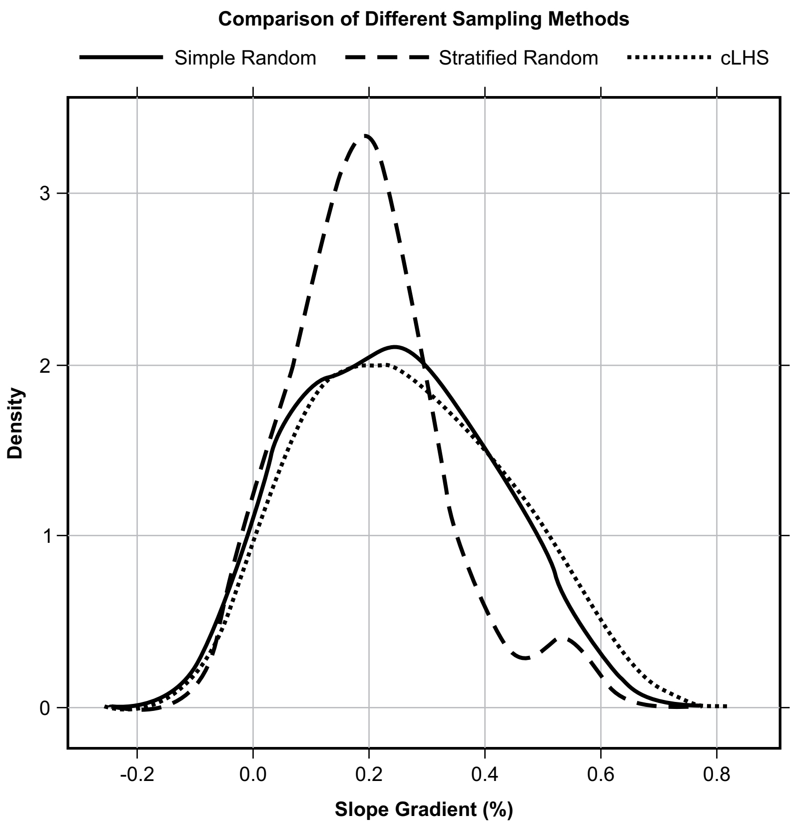
Cluster.—A cluster or group of points is selected at one or more sites, and only a portion of the available strata or primary sampling units (such as geographic strata, fields, or other separations) are sampled. If strata are an important determinant of the target soil feature(s) being evaluated, it is better to use a stratified random sample and sample all strata. Ideally, each cluster in a cluster sampling design represents the full variability of the area in question and the within-cluster variability is greater than the between-cluster variability (Lohr, 2009). When the costs of getting to a primary sampling unit are high (e.g., when sampling areas are far from a road) and the cost of individual sampling units is low, cluster sampling is highly efficient. However, it can introduce bias if clusters are not representative of the population as a whole (e.g., if a cluster is on an odd highly disturbed area) and a loss of precision if the between-cluster variability is high.

Multistage random.—Multistage random sampling is a complex form of stratification and cluster sampling. In this sampling design, only a subset of individual sampling units (such as pedons) within each cluster are selected for sampling. The individual sampling units can be arranged in order to maximize the variability, or arranged randomly, within the primary sampling unit. For example, as shown in figure 5-3, a two-stage random sampling design may stratify an area into a standard grid and randomly select a subset of strata units (first stage), then randomly select individual sample locations from within each strata unit (second stage) (Schaeffer et al., 1990; de Gruijter et al., 2006). This design offers the advantage of efficiency at reduced costs. The drawbacks include the potential for lower accuracy and precision. Successful multistage random sampling depends greatly on proper selection of strata.

Conditioned Latin hypercube.—Conditioned Latin hypercube sampling (cLHS) is a special type of stratified random sampling that uses the principle of Latin hypercube sampling conditioned with ancillary data (covariates). This sampling method selects sample locations that maximize the variability represented by multiple covariates and works on both continuous and categorical data (Minasny and McBratney, 2006). It differs from other sampling strategies, which focus on sampling geographic space, by focusing on sampling covariate feature (n-dimensional) space. This type of sampling design is efficient because it can represent the multivariate distribution of input covariates with relatively small sample sizes (Brungard and Boettinger, 2010).

This robust sampling method has been favored in digital soil mapping because it provides a representative sample based on the distribution of covariate data. Without a technique such as cLHS, obtaining a sample that is representative of the feature (n-dimensional) space becomes increasingly difficult as the number of covariates increases. Figure 5-4 compares the distribution of different sampling methods over the data range of a covariate layer.

Figure 5-4



A comparison of the distribution of simple random, stratified random, and cLHS sampling methods over the data range of a slope gradient covariate.

Conditioned Latin hypercube sampling is appropriate for any digital soil mapping project for which multiple independent covariates related to the target soil feature(s) are known or can be inferred. If soil-covariate relationships are unknown or highly uncertain, another sampling design should be used. For areas with access constraints, constrained cLHS (Roudier et al., 2012) or cLHS with fuzzy k-means clustering (Kidd et al., 2015) can be used.

The information needed to run cLHS includes: (1) covariates covering the entire project area, (2) the number of desired samples, and (3) the number of iterations needed to reach a satisfactory sampling scheme. Conditioned Latin hypercube sampling can be performed in Matlab software (MathWorks, Inc.); the R software for statistical computing (Roudier, 2011); and the USFS (U.S. Forest Service) TEUI (Terrestrial Ecological Unit Inventory) Geospatial Toolkit (Vaughan and Megown, 2015).

Predicting Soil Classes and Properties

After the optimal set of SCORPAN covariates (predictor variables) has been selected and training data have been collected, a method may be applied to the data to predict soil classes or properties. Many prediction methods are available and applicable in digital soil mapping. Considerations in choosing a prediction method include:

- Are discrete soil classes or continuous properties the goal?
- Are the training data adequate to support the desired prediction method and/or number of desired classes?
- Are the data parametric (normally distributed) or nonparametric?
- At what step in the soil survey process is the prediction being applied: pre-mapping, initial mapping, update mapping, or secondary product?
- What are the time restrictions for completing the prediction?

Classification is the process of predicting discrete classes. It can be described as the process of sorting pixels into a finite number of classes, based on their data values and distribution in feature (n-dimensional) space. Simply stated, if a pixel satisfies the criteria defining a class, the pixel is assigned to that class. This process is executed according to a classification algorithm. Depending on the type of information one wants to extract from the predictor data, classes may simply represent clusters that look statistically different to the computer (exploratory) or that are associated with known features on the ground (definitive) (refer to ERDAS Field Guide, Intergraph Corp., 2013).

Regression and interpolation methods predict continuous values rather than discrete classes. Interpolation methods model spatial patterns based on values at known locations and the assumption that locations that are closer to one another are more similar than those that are farther apart. Geostatistical approaches are forms of interpolation that rely on statistical functions rather than mathematical functions. Regression approaches use some statistical function to model the relationship between soil observations and a set of predictor variables.

Unsupervised Classification

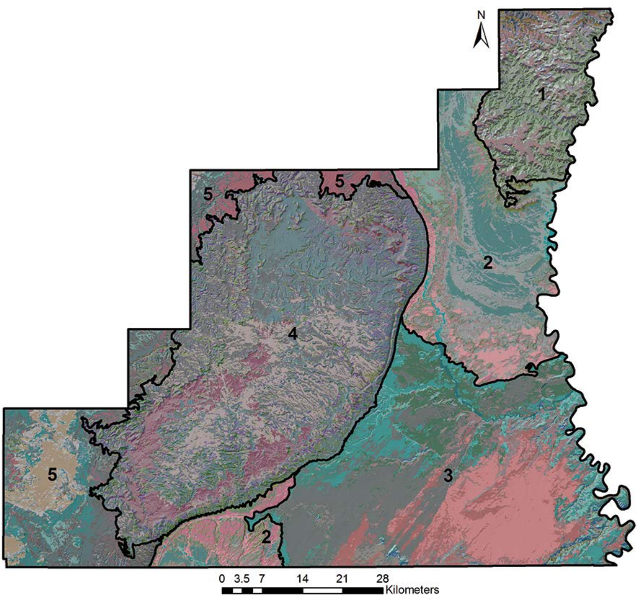
Unsupervised classification is the prediction method most reliant on computer automation presented in this chapter, and it is the only method that does not require soil observations (i.e., training data) covering the area. The algorithm uncovers statistical patterns inherent in the data and groups pixels with similar characteristics into unique clusters (classes) based on statistically determined criteria (Duda et al., 2001). The resulting class definitions are only dependent upon the predictor data representing the SCORPAN covariates and a few parameters defined at the time the classification is executed. The resulting classes must be interpreted to determine if they are meaningful in terms of soil-landscape relationships. Classes can be merged, disregarded, or manipulated based on evaluation of the class signature or definition in feature (n-dimensional) space.

Iterative Self-Organizing Data Analysis Technique (ISODATA) (Tou and Gonzalez, 1974) and k-means (MacQueen, 1967) are the most commonly used unsupervised classification algorithms and are available in many software packages. ISODATA is a modification of the k-means algorithm (Schowengerdt, 1997). Both algorithms are parametric (assuming a normally distributed dataset). They employ an iterative process that creates clusters and classifies pixels until the change in class assignment at each pixel location is small, at which point final classes are defined. The main difference between the two algorithms is that k-means requires the number of classes to be set *a priori* while ISODATA allows a range for the number of final classes to be set. ISODATA can split, merge, and delete clusters during the classification process but k-means cannot. For this reason, ISODATA is considered more computationally robust and flexible than k-means and is commonly preferred.

Unsupervised classification provides a non-subjective, data-driven method for exploring the inherent clustering of data and determining how many classes the data (predictor variables) can support. Because no prior knowledge of the area is required, unsupervised classification is a useful exploratory tool that can help direct field sampling and develop map unit concepts. However, because there is very little control over how the clusters are defined, the results may be difficult to interpret. Using an appropriate selection of predictor data based on SCORPAN covariates helps to produce the most useful results of an unsupervised classification.

Unsupervised classification is most applicable in the exploratory or pre-mapping stage of soil survey (fig. 5-5). It can help target initial field sampling and be useful in comparing mapped and unmapped areas. Unsupervised classification can be beneficial in the initial phase of digital soil mapping in determining the number of classes the predictor data can support or in determining potential classes in areas with inadequate training data. These determinations prevent using more target classes than the data can separate or support.

Figure 5-5



ISODATA unsupervised classification of both terrain and spectral data derivatives in eastern Emery County, Utah, showing natural clustering in the data and how potential classes may be distributed across the landscape. The area was divided into five subsets based on geology to minimize variability for the classification, which was run on each subset independently (10-m grid resolution). Different colors represent different classes within each subset of the survey area.

Supervised Classification

Supervised classification differs from unsupervised classification in that it requires soil observations covering the area and the target classes.

Soil observations, or training data, must be carefully chosen in order to adequately represent the target classes and produce a meaningful classification. Class definitions from training data are combined with carefully selected predictor data representing SCORPAN covariates, and the applied algorithm determines the class in which each pixel belongs.

There are multiple algorithms for supervised classification that are frequently applied in digital soil mapping. This section discusses minimum distance to means, maximum likelihood (discriminant analysis), fuzzy classification, knowledge-based classification, and predictive modeling (machine learning or statistical modeling).

Minimum distance to means.—Using this classification algorithm, candidate pixels can be classed according to the closest training class mean. This method, by definition, does not include information on the class variability. Therefore, if there are large differences in the variance of each class, the method will likely be unreliable. This method is computationally very rapid.

Maximum likelihood (discriminant analysis).—This classification is one of the most widely used standard supervised classification methods and is based on probability. Maximum likelihood uses the training class means and covariance matrices to classify candidate pixels. The probability of a candidate pixel belonging to each of the classes is calculated, and the class for which the probability is highest is assigned to the pixel. In addition, maximum likelihood allows the prior probability for the class (if known) to be specified across the dataset.

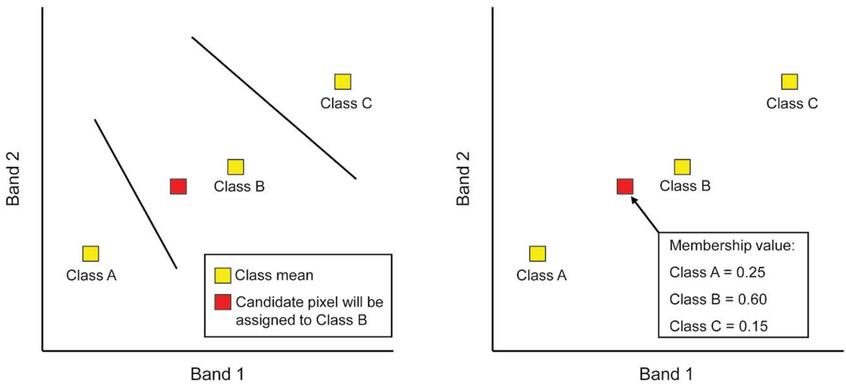
Minimum distance to means and maximum likelihood are both parametric classifiers and assume a normally distributed dataset. Therefore, training data sites and class definitions must be homogenous. These approaches to supervised classification can be useful in areas that have large extents of homogenous soils whose properties do not vary over short distances. This kind of soil landscape allows very clean class definitions and a successful classification, if training and predictor data are properly selected.

Fuzzy classification.—Homogenous soil landscapes are more simplistic for digital soil mapping. However, natural environments are more likely to contain subtle variation over short distances and non-distinct boundaries between soil types. Commonly, a candidate pixel may be mixed and have properties that overlap multiple classes.

Fuzzy set theory provides tools for working with imprecise data (Zadeh, 1965; Wang, 1990). Fuzzy classification allows information from multiple classes to contribute to the classification of a candidate pixel through the use of fuzzy logic and membership functions. In figure

5-6, for example, a candidate pixel may have a membership value of 0.25 for Class A, 0.60 for Class B, and 0.15 for Class C. The pixel is most like Class B, but information about Classes A and C is still obtained. The major difference between fuzzy classification and traditional hard classification (like minimum distance to means and maximum likelihood) is the ability to obtain information about constituent classes occurring in a mixed pixel (Foody, 2000). Due to this characteristic, fuzzy classification can accommodate nonparametric datasets.

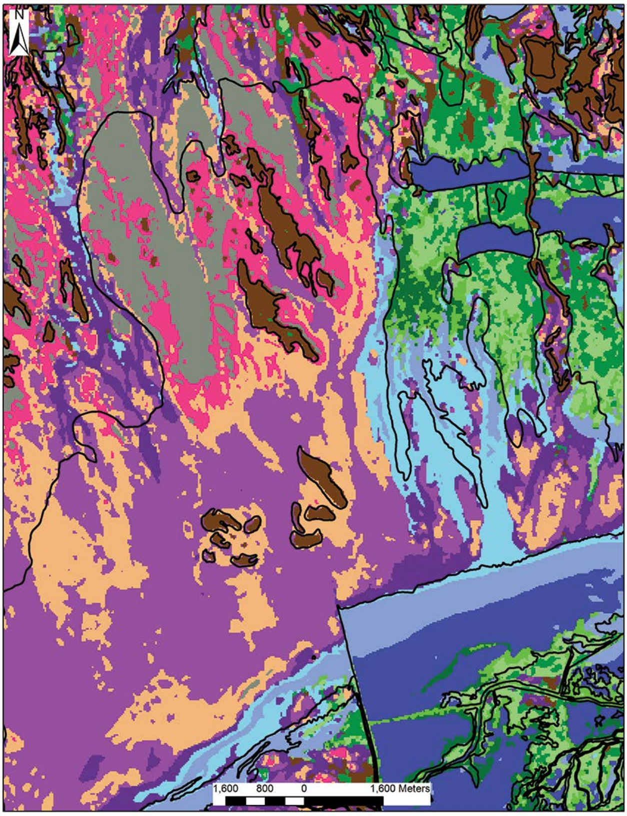
Figure 5-6



Simplistic representation of hard classification (left) and fuzzy classification (right). Hard classification requires a candidate pixel to be assigned to only one class, whichever class mean is closest. Fuzzy classification uses class means but allows candidate pixels to express properties of several classes instead of just one. (Image based on Jensen, 2005.)

Fuzzy classification has the same starting point as the other supervised classification methods, i.e., training and predictor data. However, because of its ability to handle mixed pixels, training data for fuzzy classification can represent both homogenous and heterogeneous classes (Jensen, 2005). Fuzzy classification is most useful in heterogeneous areas where variations in soil type result in mixed pixels or classes (common for soil landscapes). In the fuzzy classification process, it is possible to assign a single class to a pixel, also described as "hardening" (Zhu et al., 2001). However, information regarding constituent classes is still retained and can be used to understand the relationships in the data, refine class definitions or sort out confusion in the classification, and understand soil-landscape relationships (fig. 5-7).

Figure 5-7



Supervised fuzzy classification of Landsat imagery for an area along the east shore of the Great Salt Lake, Utah, showing a "hardened" version of the fuzzy classification (i.e., one class assigned per pixel). Results from the fuzzy classification were used to disaggregate broad map unit concepts in areas with wet and saline soils in an update soil survey project. Original Soil Survey Geographic Database (SSURGO) line work is shown in black; land cover classes representing clusters defined by soil-vegetation-moisture relationships are shown in color.

Knowledge-based classification.—Knowledge-based classification uses expert systems to represent an expert's knowledge as rules and data within a computer (Jensen, 2005). It is not only applicable to predicting soil classes but also very useful in documenting a soil scientist's knowledge about soil-landscape relationships (Zhu et al., 2001). A knowledge-based expert system consists of the following:

- Source (expert, training data, predictor data)
- Knowledge base (rule-based domain)

- Inference engine
- User

The knowledge base or rule set is constructed using the predictor data and the expert's knowledge about soil-landscape relationships and how they are expressed through the data (fig. 5-8). Specific knowledge that defines soil-landscape relationships, and subsequent soil classes, is required. An example is "badland soil complexes occur on steep eroded slopes." This knowledge can be converted into specific rules, such as "badland soil complexes occur on slope % >= 8 and have Fe band ratio value >= 67," and integrated into a knowledge base to predict the desired class (e.g., badland soil complex). In this example, the predictor data (a DEM-derived slope layer and the Fe band ratio layer derived from spectral data) are applied to the expert's knowledge (the rule) about the badland soil-landscape relationship.

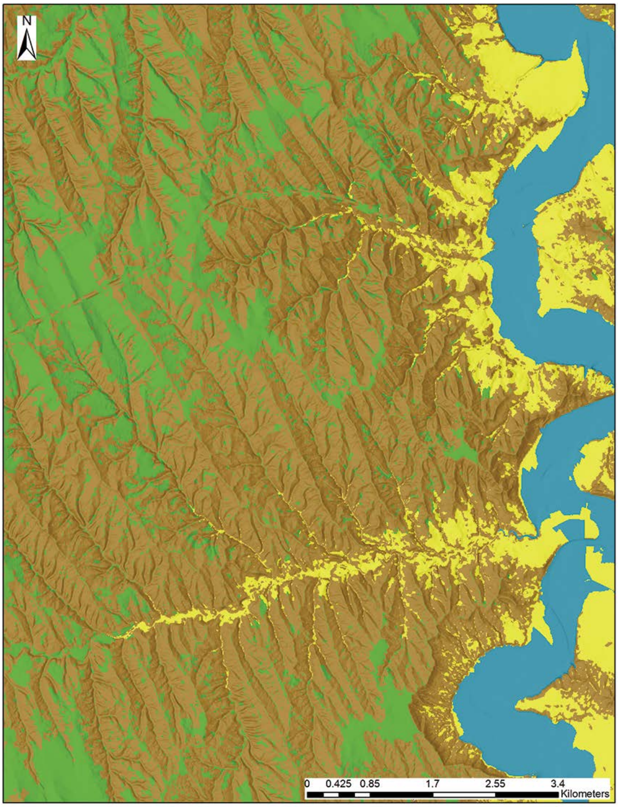
Knowledge-based classification requires the most *a priori* knowledge about soil-landscape relationships of all the classification methods presented in this chapter. It can be successful in areas where a lot of fieldwork and documentation have been completed and soil-landscape relationships are well documented and understood. Also needed are adequate predictor data to support and discriminate the specific rules defined in the knowledge base.

Knowledge-based classification is a very time-intensive approach. It requires field observations to understand the soil-landscape relationships well enough to develop specific rules for each class as well as to refine the rules in an iterative manner (as more knowledge is acquired or needed). If the resources are available, knowledge-based classification can be worth the investment, especially in terms of its ability to capture the tacit knowledge of a soil scientist.

Several software packages offer knowledge-based classifications. Some provide a hierarchical decision-tree classifier (ERDAS Imagine Knowledge Classifier) while others employ a fuzzy classification approach (SoLIM, ArcSIE). Most expert systems have the flexibility of using both continuous and categorical predictor data.

Supervised classification methods are best applied once preliminary field documentation has been collected and map unit concepts are in development. Supervised classification can be effectively applied in both initial and update soil survey projects. Since *a priori* knowledge and class definitions in the form of class signatures (or rules) are required, the methods of supervised classification discussed above can be more time intensive to initiate than classification options that are more data driven and do not require as much input initially, such as unsupervised classification and predictive modeling.

Figure 5-8

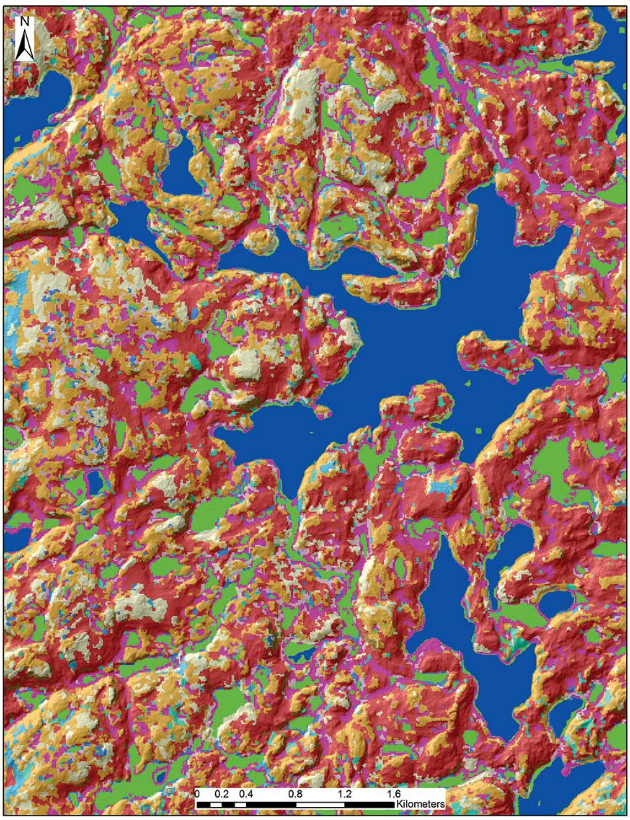


Output from a hierarchical decision-tree knowledge-based classification for four classes—fluvial soils, badland soils, uplands, and alluvial fans (shown in different colors)—in an area near the Powder River Breaks, Wyoming (Cole and Boettinger, 2007). Predictor data included both terrain and spectral data derivatives (10-m grid resolution).

Predictive modeling.—Predictive modeling (commonly referred to as statistical modeling or machine learning) for digital soil mapping is the process of developing a mathematical model that approximates the true relationship between soil properties or classes and environmental covariates in order to produce an accurate prediction. It involves choosing the necessary predictor data representing SCORPAN covariates and an appropriate model or algorithm.

Predictive models can be conceptually divided into two broad groups: classification and regression. Classification methods are used for predictions of a soil class, and regression methods are used for predictions of a continuous soil property. Within these broad groups, predictive models can be further divided based on the type of model: linear, non-linear, or tree- and rule-based. Examples of linear methods are simple linear regression and discriminant analysis. Examples of non-linear methods are multivariate adaptive regression splines and neural networks. Examples of tree- and rule-based methods are random forests (fig. 5-9) and gradient boosting machines. Kuhn and Johnson (2013) and James et al. (2014) discuss each model algorithm in depth as well as the overall process of predictive modeling.

Figure 5-9



Classification using random forests method for parent material classes in the Boundary Waters Canoe Area Wilderness, Minnesota. Predictor data included both terrain and spectral data derivatives and training data points from field data collection (5-m grid resolution).

Although many potential predictive models are available, a model that can always produce the most accurate predictions for any digital soil mapping project is difficult to find. This is because model predictive ability depends upon the structure of individual datasets and the methods used for covariate selection. The best approach is to apply several predictive models and pick the model that produces the most accurate prediction. One could start with a complex model (e.g., random forests or neural networks), then compare it to simpler models (e.g., linear regression or classification trees). If the accuracy of the simpler model is comparable to the more complex model, the simpler model can be selected. Simple models are favored for their ease of interpretation.

Overfitting can occur when applying predictive modeling for digital soil mapping. The term “overfitting” indicates that the statistical model over-emphasizes random noise instead of the underlying function. Overfit models will not produce accurate predictions. Cross-validation (a model validation method for assessing how the results will generalize to an independent data set) should be used during the model building process to avoid overfitting. Cross-validation is inherent in, or at least an option for, many algorithms.

Predictive modeling should be applied after preliminary fieldwork is complete and there is adequate training data to satisfy the model and produce an accurate prediction. It can be useful for initial or update soil survey and for soil property mapping. Depending on the model, parametric and non-parametric datasets as well as continuous and categorical data can be used in the modeling process. As a result, predictive modeling is one of the more flexible approaches to digital soil mapping prediction.

Predictive modeling provides a non-subjective, quantitative alternative to conventional soil survey and returns an estimate of prediction uncertainty based on cross-validation. However, accurate predictive modeling may require more pedon observations than are available or can be collected given project constraints. Predictive modeling works best if observations are collected using a probabilistic sampling design and if it is driven by an expert with significant knowledge of the soil system (Kuhn and Johnson, 2013).

Geostatistics

The field of geostatistics encompasses a range of techniques for modeling spatial patterns that satisfy the basic assumption that nearby objects are more related to each other than distant objects. Central to this assumption is the concept of regionalized variable theory, or the description of spatial patterns as an additive mixture of trend, spatially correlated variation, and noise. Typically, geostatistical methods are used to estimate values at unsampled locations (interpolation) based on a limited set of sampled continuous (and to a lesser extent, categorical) properties, such as A horizon pH, depth to root-restricting layer, or presence of a duripan. Geostatistics is closely related to a number of other spatial interpolation methods, such as Voronoi polygons, triangulation, natural neighbors, inverse distance weighting, trend surfaces, and splines. Geostatistical methods, however, are commonly preferred (when sufficient data are available and critical assumptions met) because they provide unbiased estimates of uncertainty.

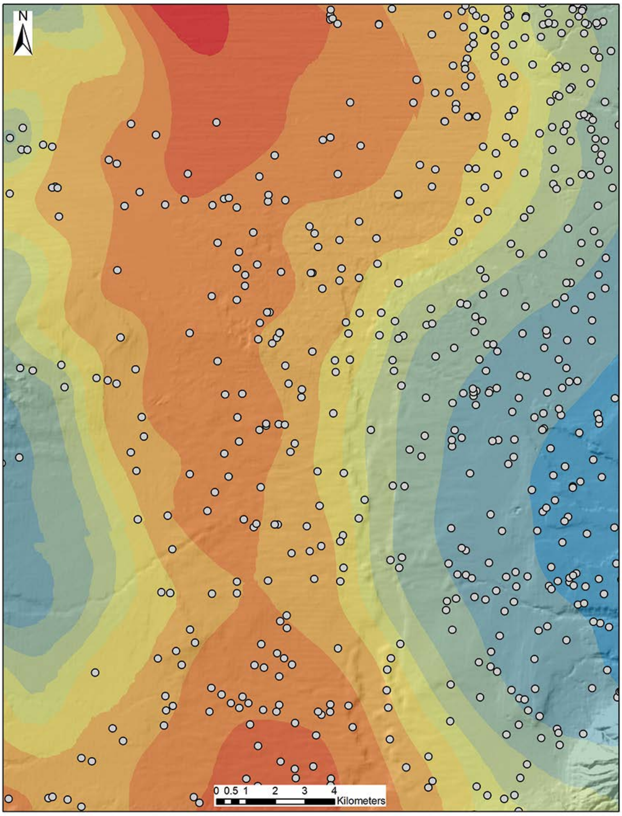
Once the appropriate data have been collected, the typical steps involved in geostatistical analysis (Webster and Oliver, 2007; Isaaks and Srivastava, 1989) are as follows:

1. Check data for outliers, extreme deviance from a normal distribution, and any spatial trend.
2. In the presence of a strong trend (e.g., elevation gradient), detrend or use hybrid approaches such as regression-kriging (Hengl et al., 2007).
3. Transform data as needed (log transformation, normal-score transformation, and logit transformation are commonly used).
4. Compute the empirical variogram (a description of how the data are correlated with distance), and check for the influence of any unusual values.
5. Fit a model to the empirical variogram, and verify that the parameters make sense.
6. Use some form of kriging to make predictions for unvisited locations.

The greatest limitation of geostatistics for soil survey is that the reliability of the variogram (and thus subsequent spatial predictions) is dependent upon both sample size and design. Typical soil survey sampling methods are commonly inadequate for reliable variogram estimation. However, geostatistics may be used for new soil products, provided that sampling design is given special attention and sufficiently large numbers of observations are collected (fig. 5-10). At least 150 samples are needed for robust variogram estimation (Webster and Oliver, 2007). The mean sampling interval (i.e., distance between samples) should be at least one order of magnitude less than the variogram range (Olea, 2009). Additionally, the application of geostatistical methods requires special consideration of anisotropy, i.e., existing trends or gradients that exhibit some form of directionality (such as the orographic effect on climate or the complex pattern of a braided stream system). It is possible to incorporate external information on such trends into the kriging process using methods such as universal kriging, kriging with external drift, or regression-kriging (Odeh et al., 1994, 1995).

Basic geostatistical methods have been implemented in the gstat package (Pebesma, 2004) for the R statistical software (R Core Team, 2013). Other commonly available software packages, such as ArcGIS, include geostatistical analysis functionality.

Figure 5-10



Interpolation using ordinary kriging of soil K concentration in the Salt Lake City Valley, Utah. Points represent locations of soil K measurements collected in the field. Concentration of K ranges from low (blue) to high (orange).

Validation and Uncertainty

Qualitative (conventional soil survey) and quantitative (digital soil mapping) soil survey methods rely on conceptual or mathematical models to describe soil spatial distribution. These models are approximations of reality and are thus subject to uncertainty. Due to the quantitative nature of digital soil mapping, predictions of soil classes or properties lend themselves to quantitative assessments of accuracy and uncertainty. Communicating the accuracy and uncertainty associated with soil spatial predictions is imperative and should be an integral part of any digital soil mapping project, particularly given that soil information is used in decision making and risk assessment.

Accuracy

All soil maps are approximations of reality, such that the values depicted on a map will deviate to some extent from true values. Accuracy estimates are therefore necessary to quantify prediction quality. Prediction accuracy is the difference between the predicted value at a location and the measured value at the same location (Brus et al., 2011). Desirable predictive models have high prediction accuracy (i.e., small differences between predicted and observed values).

Prediction accuracy is quantified differently depending on whether soil classes or soil properties are being modeled. Soil class prediction accuracy is quantified using overall accuracy, user's accuracy, and producer's accuracy. These metrics are best understood by reviewing a confusion matrix (table 5-3) that compares the number of correctly and incorrectly predicted observations for each class. Overall accuracy is the proportion of correctly classified observations in the entire dataset. User's accuracy (also known as "errors of commission" or precision) is the proportion of a predicted class that matches the observed class. Producer's accuracy ("errors of omission" or specificity) is the proportion of an observed class that matches the predicted class (Congalton, 1991; Kuhn and Johnson, 2013).

Table 5-3 shows a confusion matrix of three modeled soil subgroup classes, modified from data presented in Brungard et al. (2015). Observation numbers were 26 Ustic Haplargids, 2 Ustic Paleargids, and 21 Ustic Torriorthents. Overall accuracy was calculated by summing the correctly predicted observations (matrix diagonal; 11) and dividing by the total number of observations (49). User's accuracy for each class was calculated by dividing the correctly predicted observations for each class by the row totals. Producer's accuracy for each class was calculated by dividing the correctly predicted observations for each class by the column total. Overall accuracy was relatively low because the Ustic Paleargid class was never modeled correctly (an effect of low numbers of training observations). Low overall accuracy masks the relatively high accuracy of the other two classes.

Table 5-3

Confusion Matrix of Three Modeled Soil Subgroup Classes

Predicted soil class	Observed soil class			Total correctly predicted	User's accuracy
	Ustic Hapl-argid	Ustic Pale-argid	Ustic Torri-orthent		
Ustic Haplargid	6	1	1		0.75
Ustic Paleargid	0	0	0		0.00
Ustic Torriorthent	1	0	5		0.83
				11	
Producer's accuracy	0.86	0.00	0.83		Overall accuracy: 0.22

It is important to note that the above accuracy metrics are all threshold-dependent, i.e., they depend upon a cutoff threshold above which observations are classified as belonging to a particular soil class. All predictive models output probability or membership values, which are then classified as belonging to a particular soil class if they are above some threshold (commonly 0.5 by default). However, if this threshold is changed, then validation observations may be included or excluded from a particular class and the confusion matrix and resulting accuracy metrics altered. Though most commonly used for two class predictions, threshold-independent metrics, such as the area-under-the-curve (AUC), provide an estimate of prediction accuracy over all threshold values (Kuhn and Johnson, 2013).

Accuracy of soil property predictions is typically quantified using mean square error (MSE), root mean square error (RMSE), and coefficient of determination (R^2). Mean square error is the average squared difference between predicted and measured values. Because MSE is a squared difference, the square root of MSE (RMSE) commonly is used to report accuracy in the same units as the original measurements (Kuhn and Johnson, 2013). Smaller RMSE indicates a more accurate model. The coefficient of determination (R^2) is a measure of the correlation between observed and predicted values and commonly is interpreted as the proportion of the data explained by a model. Caution is needed when using R^2 because it is a measure of correlation, not accuracy, and is dependent upon the variation in the test set (Kuhn and Johnson, 2013).

Validation observations (also known as reference observations) necessary to calculate prediction accuracy metrics can be derived from independent validation data, internal model performance measures, or data-splitting methods. Independent validation data are observations gathered independently from data used for model building (the training data set). Independent validation is the best way to assess prediction accuracy because it is the only way to determine true prediction accuracy. Independent validation data should be gathered using probabilistic sampling methods to avoid bias. Sampling schemes for validation can be found in Brus et al. (2011) and de Gruijter et al. (2006), and methods for calculating the required number of observations can be found in Congalton (1991).

Although independent validation data are preferable for accuracy assessment, in some cases it is not possible to collect such data (such as with legacy data) and other methods are required. Internal model performance measures (also termed calibration accuracy) are used for model tuning. They indicate how well the model matches the data. Examples of internal model performance measures include the out-of-bag error (OOB) used in the random forests tree-based model and the mean squared error commonly used in many regression models (James et al., 2014). Internal model performance measures are useful for assessing model parameters, but such measures commonly overestimate actual prediction accuracy because statistical models are designed to minimize (or maximize) these internal accuracy measures. Prediction accuracy should not be inferred solely from internal model performance measures.

Related to internal model performance measures are data-splitting methods. Data-splitting methods involve reserving a portion (commonly 10 to 30 percent) of the available training data to use only for validation. Using an observation for both model training and validation is redundant and strictly prohibited. In data splitting, the reserved portion of the data is only used in model validation and not in model training/building. While data-splitting practices are common, there is no guarantee that a different subset of the training data would result in the same accuracy estimates. A better alternative is to use cross-validation, which repeatedly divides the training data into *n* (commonly 5 or 10) training and validation subsets and thus evaluates many alternate versions of the data (Kuhn and Johnson, 2013). Cross-validation results in prediction accuracy estimates with associated variability (e.g., standard deviations). If the initial field-sampling method was biased, cross-validation accuracy estimates may not adequately capture true prediction accuracy because cross-validation relies strictly on the data used in modeling.

Estimates of prediction accuracy are necessary for quantifying digital soil mapping prediction quality and should be included as a vital component of any digital soil mapping project. Measures for accuracy calculation are available in many software packages and commonly are included in the execution of prediction models.

Uncertainty

Uncertainty in traditional soil survey results from the scale of mapping (e.g., order 1 vs. order 3), the placement of map unit lines, and the inclusion of similar soils. This uncertainty is quantified using map unit composition (e.g., Map unit 1 is 55% soil A, 30% soil B, and 15% soil C).

Uncertainty in digital soil mapping results from several sources: (1) positional accuracy of the pedon location (particularly for legacy pedon observations); (2) covariate accuracy (e.g., vertical uncertainty of a digital elevation model); (3) soil class or property measurement (e.g., taxonomic classification or laboratory analysis); and (4) model structure (e.g., using a linear model for curvilinear data).

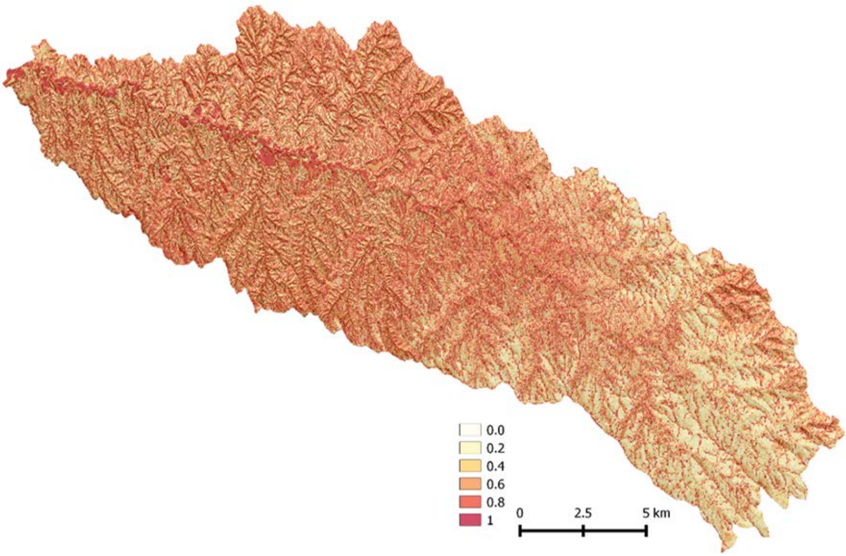
Digital soil mapping uses memberships or probabilities to quantify prediction uncertainty when modeling soil classes. Soil class memberships/probabilities indicate the similarity of soil class occurrence in each grid cell. Digital soil mapping produces a membership/probability grid for each modeled soil class. Confusion between soil class predictions is quantified with the confusion index (CI):

$$CI = [1-(\mu_{max} - \mu_{(max-1)})]$$

where μ_{max} is the membership/probability value of the class with the maximum membership/probability and $\mu_{(max-1)}$ is the second-largest membership/probability value. If the memberships/probabilities of the two most likely classes are similar (e.g., 0.3 and 0.2) then the CI will approach 1, indicating high confusion about the class to which the prediction should belong (fig. 5-11). If the memberships/probabilities of the two most likely classes are dissimilar (e.g., 0.7 vs. 0.1) then the CI will approach 0, indicating little confusion between classes (Burrough et al., 1997; Odgers et al., 2014).

Digital soil mapping uses prediction intervals to quantify uncertainty in soil property predictions (fig. 5-12). Prediction intervals (not confidence intervals, which measure uncertainty about the mean) indicate the range in values within which the true value is likely to occur (Malone et al., 2011). Digital soil mapping most commonly uses 90% prediction intervals, which indicate the range in values in which a new measurement will be found 9 times out of 10. Prediction intervals are most commonly shown as companion maps, where the lower prediction

Figure 5-11



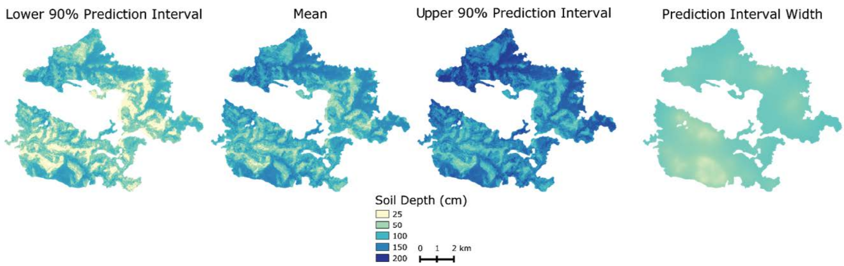
Example of the confusion index for soil class prediction over approximately 300 km² in the Powder River Basin, Wyoming. Confusion index values near 1 indicate areas of uncertainty in soil class spatial predictions. Figure adapted from Brungard et al. (2015).

interval, mean, and upper prediction interval are shown side by side (fig. 5-12). In some cases, the prediction interval width is also provided to indicate the spatial variability of uncertainty (fig. 5-12). Although less common, another option for displaying soil property prediction uncertainty is through "whitening" (Hengl, 2003, 2007), i.e., predictions whiten/pale based on the uncertainty so that highly uncertain predictions approach the color white. Methods for calculating prediction uncertainty are readily available in many software packages.

Applications of Digital Soil Mapping

Digital soil mapping is widely used to predict soil classes and properties and produce a soil map. However, the process of generating spatially explicit predictions of natural phenomena using quantitative relationships between training data and predictor variables can be applied to create a broad spectrum of information products. The following

Figure 5-12



Example of prediction intervals and prediction interval width for soil depth to a restricting layer over approximately 50 km^2 in San Juan County, Utah. Wider prediction intervals indicate greater uncertainty.

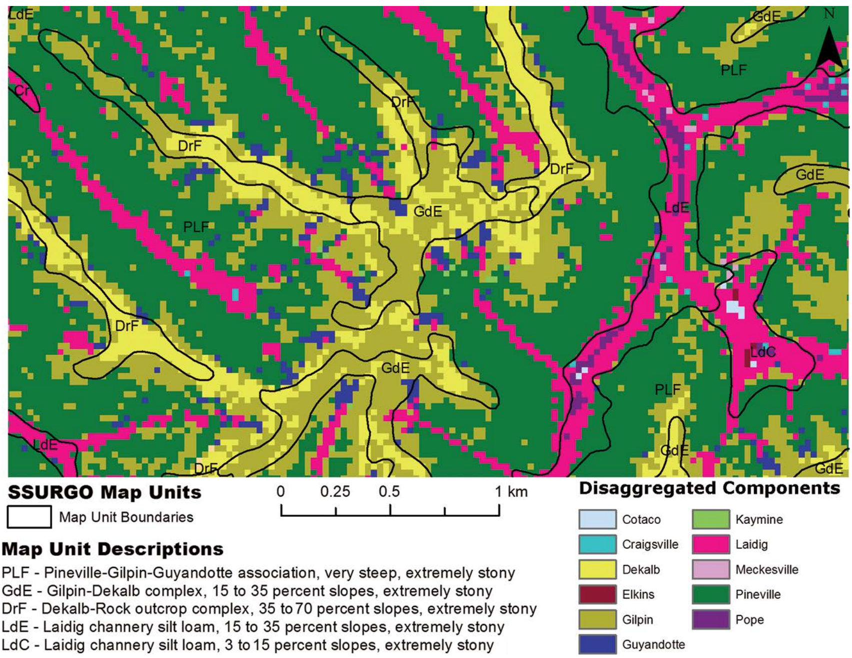
paragraphs discuss examples of the application of digital soil mapping in pedology and related fields to produce information products other than soil maps.

Raster vs. Polygon, Disaggregation, and Evaluation of Existing Maps

A fuzzy classification of Landsat 7 spectral data was applied in an update soil survey of wet and saline map units along the east shore of the Great Salt Lake, Utah, specifically for disaggregation of a few very broad map units. The disaggregated product showed the distribution of soil components (tied to land cover type) with an overall map accuracy of 88%. It highlighted the additional information a raster product can convey that a vector product cannot. The disaggregated raster product allowed for refinement of map unit concepts and line work, particularly in areas previously lumped into a miscellaneous "Playa" map unit, which had no soil information to support it. This survey area is important for wetland preservation and migratory habitat for large populations of birds and is experiencing pressure from encroaching development (Kienast-Brown and Boettinger, 2007).

Disaggregation of the Soil Survey Geographic Database (SSURGO) legacy data into maps at soil component level was completed for two West Virginia counties using soil-landscape knowledge, data mining, and predictive modeling (Nauman and Thompson, 2014). Descriptions of the soil-landscape relationships stored in the SSURGO database for the two survey areas were used, along with elevation data and derived geomorphic indices, to build a set of representative training areas for all soil components. The training areas were used in classification tree ensemble models with additional environmental covariates to predict soil series extent (fig. 5-13). Underlying prediction frequency surfaces were also generated from the models and used to create continuous soil property maps. Model predictions agreed with validation pedons 22 to 44% of the time. This study demonstrates how disaggregation techniques may be used to update soil surveys.

Figure 5-13



Example of a disaggregation of SSURGO in West Virginia (modified from Nauman and Thompson, 2014) showing the hardened classification of soil series components with an overlay of the original map unit boundaries.

Predicting Biological Soil Crusts

Biological soil crusts are communities of cyanobacteria, algae, microfungi, mosses, liverworts, and lichens at the soil surface (Soilcrust.org, 2016). They stabilize soil, minimize wind and water erosion, and are important sources of soil N and organic C in arid and semiarid ecosystems (Belnap et al., 2001). Biological soil crust level-of-development (LOD) classes represent a development sequence from low to high, with higher classes indicating greater cyanobacteria development (Belnap et al., 2008). Spatial predictions of low, moderate, and high LOD classes were completed for an area surrounding and including Canyonlands National Park, Utah, to assist in management of this important resource (Brungard and Boettinger, unpublished data).

Spatial predictions of the presence or absence of biological soil crust LOD class were derived using unweighted model averaging (Malone et al., 2014) of five statistical models: stochastic gradient boosting, random forests, maximum entropy, generalized linear models, and generalized additive models. Observations of biological soil crust used in model development were obtained during a 2006-2009 soil survey update of Canyonlands National Park, Utah.

Prediction uncertainty was calculated as the standard deviation of the combined probability predictions from each model. Lower prediction uncertainty indicates more robust predictions. Prediction quality was assessed using concordance. Concordance is the number of models predicting class occurrence in each raster cell. High concordance values (e.g., 5) indicate areas where all models predict biological soil crust presence and thus identify areas where greater confidence may be placed in presence predictions. Conversely, low concordance values (e.g., 1) indicate areas where only a few models predict biological soil crust presence and thus identify areas where less confidence may be placed in spatial predictions.

Predicting Ecological Sites

Correlating ecological sites with soil map units is an important component of soil mapping in the United States. It provides an understanding of how biotic and abiotic factors in the environment interact and influence one another. (Appendix 4 discusses ecological site descriptions.) Ecological sites are considered a vital part of many land management decisions (USDA-NRCS, 2008). Several studies focused on predicting distribution of vegetation types, to assist in understanding spatial relationships of ecological sites, have been conducted in Rich County, Utah. A selected set of elevation (DEM) and spectral (Landsat) data derivatives were used as input to logistic regression models to produce predictions of vegetation types that play a key role in ecological site identification (Peterson, 2009). An accuracy of 71% was reported based on an independent validation data set.

A subsequent study in Rich County, Utah, used a combination of elevation and spectral derivatives and random forests classification to predict five dominant vegetation types (Stam, 2012). Reported overall accuracies were between 81% and 98%. Prediction of ecological sites and states was also explored in this same study using Landsat spectral data derivatives and supervised classification, specifically the maximum likelihood classifier. A similarity index was calculated, based on the Mahalanobis distance generated during the classification, and related to various states (6 total) of the ecological site. The similarity index was successful in defining where different states of a given ecological site occur on the landscape, with a reported accuracy of 65%.

Predicting Rare Plant Habitat

Shrubby reed-mustard *(Schoenocrambe suffrutescens),* a U.S. federally listed endangered shrub endemic to the Uinta Basin, Utah, faces habitat loss due to fossil fuel energy development and extraction. Random forests models and digital environmental covariates were used to identify potential shrubby reed-mustard (SRM) habitat (Baker et al., 2016). A three-step approach was used to create the final predictive map. First, soil properties measured in the field were used to predict SRM presence or absence (out-of-bag [OOB] error of 10%). Second, these soil properties were correlated to elevation and spectral data, including a DEM, DEM derivatives, and Landsat 5 TM imagery, to predict SRM habitat onto a spatial extent and generate training data points for a final model (OOB error of 28%). Calcium carbonate equivalent, silt content, and dry color value were strongly correlated with yellowness from the Tasseled Cap transformation, 3/2 normalized difference ratio, and 3/1 normalized difference ratio (spectral band ratios typically associated with geology and carbonate content). Third, the spectral and elevation data were used to create a final predictive raster of potential SRM habitat with OOB error of 23%, validated by an independent dataset of SRM locations. Variable importance plots were used in all models to indicate the mean decrease in accuracy for each predictor variable. The most important predictor variables were selected and reduced to a subset by manual stepwise elimination to obtain the best model fit with the fewest variables. The final model can be used to identify potential habitat across a large area, especially where remote or rugged terrain make access difficult and time- and labor-intensive. Once soil and site data are located for potential habitat areas, they can be used to verify SRM habitat suitability and focus conservation or restoration efforts.

Summary

Digital soil mapping uses field and laboratory observations coupled with spatially explicit environmental covariates (SCORPAN) and modern computer technology to predict soil classes or properties. It complements and builds upon the collective knowledge and expertise accumulated over many decades of conventional soil survey work. Major advantages of digital soil mapping include:

- The most accurate model that resources can support through the iterative process of development and testing can be used to create the final soil map. Models can be refined until the resulting soil map meets accuracy and uncertainty standards.
- The uniform application of the model across the project area results in a consistent soil map.
- The degree of accuracy and uncertainty associated with the soil map can be expressed quantitatively.
- Soil information is captured for each grid cell rather than aggregated for entire polygons. As a result, there is a more detailed portrayal of the short-range soil variability over the landscape.
- The models developed to predict soil classes or properties are an effective way to capture and preserve expert knowledge about soil and landscape relationships.

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CHAPTER 6

Tools for Proximal Soil Sensing

By Viacheslav Adamchuk, McGill University; Barry Allred, USDA–ARS; James Doolittle, USDA–NRCS; Katherine Grote, Missouri University of Science and Technology; and Raphael Viscarra Rossel, CSIRO Land and Water

Introduction

Proximal soil sensing is a collection of technologies that employ a sensor close to, or in direct contact with, the soil. The sensor measures a soil property directly or indirectly. Viscarra Rossel et al. (2011) provide a description of proximal soil sensing, sensing technologies, and the soil properties these technologies can measure. This chapter describes different types of proximal sensing tools that can be used to map soil attributes of importance for agriculture and natural resource management.[1]

Soil properties vary in space and over time. As a consequence, they are seldom adequately described at field and landscape scales by traditional soil survey tools. Traditional methods of soil sampling and analyses provide detailed information at specific locations. This information, however, is limited in number, volume, and spatial coverage. See chapter 3 for a discussion of the standards and protocols used to examine and describe soils at the pedon scale in the field. At field and landscape scales, the characterization of the spatial and temporal variations is prohibitively time-consuming, expensive, and impractical using traditional point-sampling methods alone. Remote sensing (e.g., satellite images and aerial photos) can provide excellent spatial coverage, but measurements are mostly indirect and typically limited to the top 5–6 cm of soil. In addition, resolution is generally

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[1] Trade or company names used in this chapter are provided as examples for informational purposes only. This use does not constitute an endorsement by USDA or the contributing authors of this chapter.

too coarse to characterize the spatial variability of soil properties at intermediate field and landscape scales. Because of these limitations, proximal soil sensing is becoming increasingly popular as a way to fill in the data gap between high-resolution point data and the lower resolution remote-sensing data (Adamchuk et al., 2011; Adamchuk and Viscarra Rossel, 2011).

Data from proximal soil sensing technologies can be used in soil surveys of order 1, 2, or 3. They can be used to show how one or more soil properties vary over a portion of the landscape, to help estimate the range in property values for a particular soil series or map unit component, to refine the boundaries of soil map unit delineations, and to identify the location and extent of contrasting soil components within soil map unit delineations. Some of the methods can be used to document soil properties at specific locations (point data) when describing soil profiles. Table 6-1 shows the general application of various proximal soil sensing methods to soil survey activities. Definitions of soil survey orders are given in chapter 4.

This chapter is divided into two major parts. The first part discusses three geophysical methods: ground-penetrating radar, electromagnetic induction, and electrical resistivity. These methods have been used widely in the United States by the National Cooperative Soil Survey (NCSS) to document soil property variability in specific landscape settings and to identify the locations of contrasting soil components within map units. The second part discusses nine other proximal soil sensing methods that, to date, have had limited application by the NCSS. These technologies are included in this chapter because they have potential for expanded future use, especially in high-intensity surveys (i.e., order 1) and in recording properties when describing soil profiles.

Common Geophysical Methods

The three geophysical methods most commonly used for soils and agriculture are ground-penetrating radar (GPR), electromagnetic induction (EMI), and electrical resistivity (ER) (Allred et al., 2008a and 2010).

Geophysical methods exploit contrasts in physical properties to indirectly measure, profile, and monitor differences in physico-chemical soil properties; locate soil, lithologic, and stratigraphic boundaries; and characterize soil patterns and features. Examples of the physical

Table 6-1

Methods of Proximal Soil Sensing and Their Primary Application in Soil Survey

[Order 1 surveys are high-intensity or special use surveys. Applications for order 1, 2, and 3 surveys include map unit boundaries, component composition, and/or spatial distribution of properties (see chapter 4). Applications for point data include documentation of static or temporal soil properties.]

Method	Primary soil survey application		
	Map unit (spatial) data		Point data
	Order 1	Orders 2 & 3	
Ground-penetrating radar	X	X	
Electromagnetic induction	X	X	
Electrical resistivity	X	X	
Magnetometry	X		
Magnetic susceptibility	X		
Portable X-ray fluorescence			X
Time domain reflectometry			X
Optical reflectance	X	X	X
Gamma-ray spectroscopy	X	X	X
Mechanical interactions	X		X
Ion-selective potentiometry	X		X
Seismic	X	X	

properties include dielectric permittivity, apparent electrical conductivity or resistivity, and magnetic susceptibility.

ER and EMI methods were initially used to assess soil salinity, but their use greatly expanded with the development of precision agriculture in the 1990s. Since the late 1970s, GPR has been used extensively by the National Cooperative Soil Survey as a quality-control tool to improve soil interpretations. Recent technological improvements have increased the use of these and other geophysical methods in soils. Improvements include instrumentation, computational capabilities, data processing, interpretative and display methods, and integration with other technologies (e.g., global positioning systems).

Ground-Penetrating Radar (GPR)

Ground-penetrating radar is an impulse radar system. It transmits short pulses of very high and ultra-high frequency (from about 30 MHz to 1.2 GHz) electromagnetic energy into the soil and underlying strata from an antenna. When these pulses contact an interface between layers with contrasting dielectric permittivity, a portion of the energy is reflected back to a receiving antenna. The more abrupt and contrasting the difference in dielectric permittivity, the greater the amount of energy that is reflected back to the receiving antenna. The receiving antenna records the amplitude of the reflected energy as a function of time, and the variation in amplitude is displayed on a video screen and stored for playback and processing. Interpretation of GPR data is generally performed by noting the arrival time of a reflection from a subsurface interface and associating the reflection with a known or suspected soil interface. To interpret the depth to an interface, the velocity of the pulse through the soil must be determined or the interface depth must be obtained by ground-truth measurements.

Ground-penetrating radar is most effective at sharp interfaces between materials of contrasting dielectric permittivity. Although influenced by bulk density and mineralogy, dielectric permittivity in soil is primarily controlled by water content. Thus, GPR is useful for imaging the interfaces between layers that contain different amounts of water. It is also very effective in determining the location of air-filled or water-filled voids (such as pipes) and metallic objects. GPR works best in coarse grained soils because electrically conductive materials (i.e., soils with high clay content and saline soils) weaken the signal.

A disadvantage of GPR is that resolution decreases with increasing depth of investigation and decreasing antenna frequency. Although higher frequency antennas provide higher resolution, they also provide lesser depth of investigation. Penetration depth is inversely proportional to the sounding frequency. In general, penetration with low-frequency antennas is less than 30 cm in saline soils and less than 1 m in wet, clayey soils (Daniels, 2004). In dry, sandy and gravelly soils, however, GPR penetration can exceed 50 m with low-frequency antennas (Smith and Jol, 1995). Profiling depths as great as 10 m have been recorded in organic soil materials that have very low electrical conductivity.

The speed, field economy, high resolution, and continuous measurement of GPR are assets in soil investigations. Modern GPR systems are self-contained and portable and have integrated GPS and real-time data visualization capabilities, which allow greater mobility and more effective use (fig. 6-1).

Figure 6-1

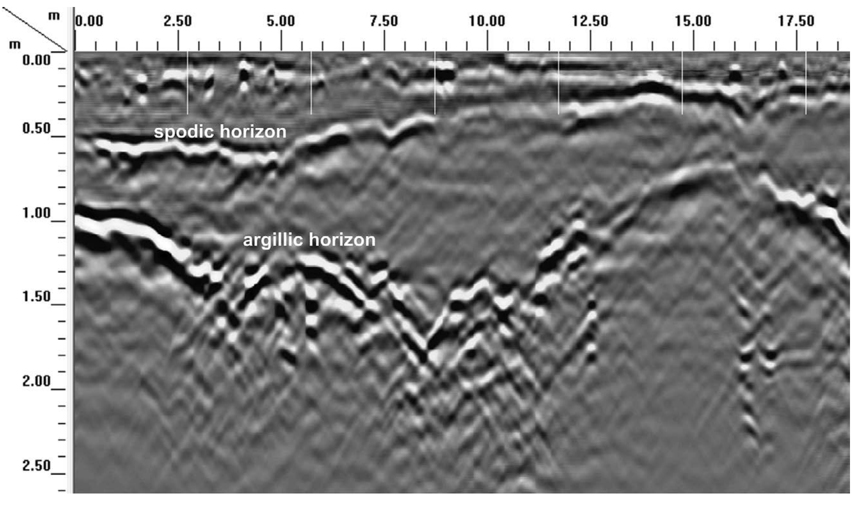
Modern GPR systems are light-weight, highly mobile, and integrated. A typical GPR system consists of a control unit (located beneath blue visor on the cart) with an antenna (orange box beneath the cart).

Examples of GPR Use in Soil Survey

Ground-penetrating radar has been used by soil scientists principally in order 1, 2, and 3 soil surveys. It serves as a quality control tool in documenting the taxonomic compositions and improving the interpretations of soil map units (Doolittle and Butnor, 2008). In these applications, GPR documents the presence, depth, lateral extent, and variability of diagnostic subsurface horizons. Typically, strong radar reflections are produced by abrupt interfaces between highly contrasting soil materials. Where soil conditions are suitable, GPR can determine the depth to contrasting master (B, C, and R) subsurface horizons and layers. Other soil horizons and layers have also been identified with GPR. Examples include buried genetic horizons, dense root-restricting layers, frozen soil layers, illuvial accumulations of organic matter, and cemented or indurated horizons. Ground-penetrating radar generally is unable to detect subtle changes in soil properties (e.g., structure, porosity, and texture), transitional horizons (e.g., AB, AC, and BC), or vertical divisions of master horizons. However, GPR has been used to infer distinct vertical changes in soil color associated with abrupt and contrasting changes in organic carbon content.

Figure 6-2 is a radar record from an area of Pomona soils (sandy, siliceous, hyperthermic Ultic Alaquods) in north-central Florida. The upper boundaries of the spodic and argillic horizons are abrupt and separate contrasting soil materials. They therefore produce high-amplitude reflections. On this radar record, the spodic horizon provides a continuous reflector that varies in depth from about 20 to 60 cm. The upper boundary of the argillic horizon is highly irregular and varies in depth from about 60 to 150 cm. Generally, argillic horizons provide smooth, continuous reflectors at more uniform depths than those shown in this example. The irregular topography of the upper boundary of this argillic horizon is attributed to underlying dissolution features associated with karst. The presence and varying depths to these two subsurface soil horizons were used to distinguish different soils along the radar traverse line.

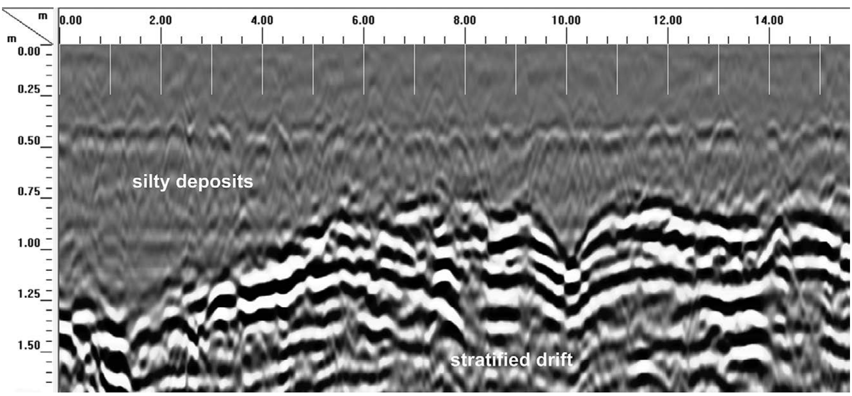
Figure 6-2



A radar record showing well expressed spodic and argillic horizons in a Pomona soil in north-central Florida.

The radar record in figure 6-3 shows an abrupt and contrasting discontinuity that separates a silty eolian mantle from underlying sandy outwash. This stratigraphic discontinuity is an easily identified, laterally continuous, high-amplitude reflector that ranges in depth from about 85 to 150 cm across the radar record. In southern Rhode Island, the depth to the discontinuity was used to distinguish areas of Bridgehampton soils (coarse-silty, mixed, active, mesic Typic Dystrudepts) and Enfield soils (coarse-silty over sandy or sandy-skeletal, mixed, active, mesic Typic Dystrudepts). Soil materials on different sides of this discontinuity differ from each other substantially in particle-size distribution, bulk density, and pore-size distribution. In addition, linear reflections in the lower material helped to confirm that the material is glacial outwash rather than till. Typically, till has a chaotic radar signature characterized by an abundance of point reflectors (from cobbles and boulders) and an absence of linear reflectors (which are typical for layered deposits). On this radar record, a dense Bw horizon appears as a weakly expressed linear reflector at a depth of about 35 cm.

Figure 6-3



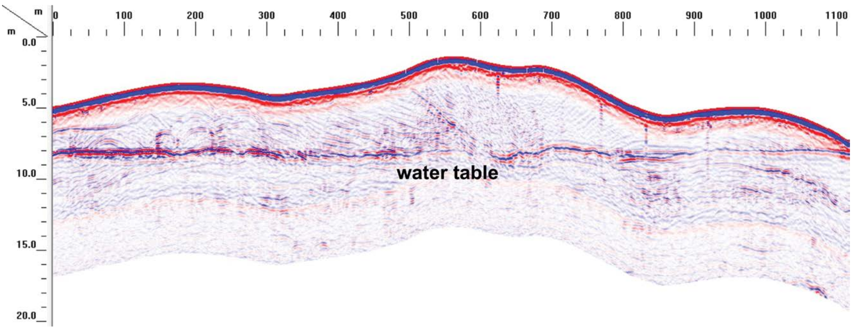
A radar record showing a discontinuity separating a loamy eolian mantle from sandy glacial outwash in southern Rhode Island.

Hydropedological modeling requires detailed information on the depth and movement of water beneath soil landscapes. Sandy soils have a narrow capillary fringe, resulting in a relatively sharp interface between unsaturated and saturated soil materials. As a result, water tables are often distinguishable on radar records from sandy soils.

Figure 6-4 is a surface normalized (i.e., elevation data were used to show topographic changes) radar record. It shows a low dune composed of very deep, excessively drained Oakville soils (mixed, mesic Typic

Udipsamments) in northwestern Indiana. On this radar record, the water table can be seen as a continuous, high-amplitude reflector between depths of about 2.5 and 4.0 m. Repetitive GPR measurements throughout the year can increase the level of confidence in hydropedological site assessments and reduce the number of wells needed for studies of water tables and ground-water flow.

Figure 6-4



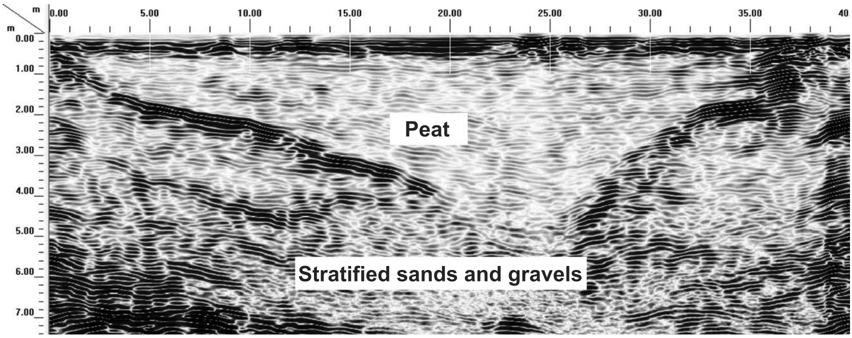
A terrain-corrected radar record in which a water table provides a high-amplitude reflector in a dune field in Indiana.

Ground-penetrating radar has been used extensively on peatlands. GPR applications in peatlands include estimating the thickness and volume of peat deposits; distinguishing layers that differ in degree of humification, bulk density, and volumetric water content; characterizing underlying mineral sediments, stratigraphy, and hydrology and their relationships to present vegetation; and classifying and mapping organic soils.

Figure 6-5 is a radar record from a fen in a kettle depression in southeastern Massachusetts. The fen is an area of very deep, very poorly drained Freetown soils (dysic, mesic Typic Haplosaprists). Abrupt and strongly contrasting changes in water content make the interface between organic and mineral material distinguishable on the radar record. This interface forms a conspicuous reflection that varies in depth from about 0.36 meter to 5.4 meters.

In addition to detecting subsurface interfaces, GPR can be used as a tool for quantitatively mapping soil water content (Huisman et al., 2003). This mapping can be done because of the strong dependence of dielectric permittivity on soil water content. The dielectric permittivities of air and

Figure 6-5



The thickness of organic soil materials that overlie coarse textured glacial outwash is evident on this radar record from an area of Freetown soils in southwestern Massachusetts.

water are 1 and ~80, respectively. The permittivity of most mineral soils ranges from ~3 to 40, depending on soil water content. The permittivity of dry mineral soils ranges from 3 to 5. Several petrophysical models are available to convert measurements of dielectric permittivity to estimates of soil water content. One of the most commonly used models was developed by Topp et al. (1980). This empirical model was developed using a range of agricultural soils. Because the dielectric permittivity is the only input, the model can be easily applied to sites that have significant soil heterogeneity or limited soil characterization. Topp's empirical model for estimating soil water content (θ) from dielectric permittivity (*K*) is expressed as:

$$\theta = (5.3 \times 10^{-2}) + (2.29 \times 10^{-2})K - (5.5 \times 10^{-4})K^2 + (4.3 \times 10^{-6})K^3 \qquad [1]$$

Other empirical relationships have been developed for different soil textures. Soil-specific empirical relationships can also be developed using data from GPR or a time domain reflectometer (TDR). Another type of petrophysical relationship uses the volume fraction and measured permittivity of each soil component (soil solids, air, and water). However, these volume-averaging relationships typically require porosity as an input, which may vary widely across a site and is often unknown (Roth et al., 1990).

Dielectric permittivity can be estimated from measurements of the electromagnetic velocity in most earthen materials. Unless the material is very electrically conductive, the dielectric permittivity depends only upon the velocity of the radar signal. In materials that have moderate to low electrical conductivity, the relationship between the radar signal velocity (*v*) and dielectric permittivity (*K*) is:

$$K = (c/v)^2 \quad [2]$$

In equation 2, *c* is the speed of light (Conyers, 2004). Several methods are available for measuring velocity. The most common method uses reflected energy from a subsurface interface. If the depth to a subsurface reflector is known, the velocity may be calculated using the time needed for the energy to travel from the transmitter to the reflector and then back to the receiver. This travel time can be determined by the arrival time of a reflection viewed on a radar record. If the depth to a reflector is not known, the velocity can be obtained by performing a variable-offset survey. This method requires separate transmitting and receiving antennas. In a variable-offset survey, the transmitting and receiving antennas are initially placed close together and then incrementally moved further apart with each measurement. The velocity can be measured by analyzing the travel time of the reflected signal as a function of distance as the antennas are moved apart. Although variable-offset surveys provide important information on velocity and reflector depth, they are time-consuming and thus cannot be used to monitor large areas.

GPR reflection techniques can also be used to provide non-continuous measurements of velocity and thus soil water content. These measurements can be taken when a reflection hyperbola is created in the GPR record by isolated subsurface objects (e.g., stones and metal fragments) or by buried pipes that trend perpendicular to the GPR traverse. Reflection hyperbolas appear on GPR records as upside-down U shapes. Curve fitting procedures for reflection hyperbola can be employed to estimate the velocity. These procedures adjust a modeled shape to match the shape of the reflection hyperbola on a radar record. This fitting yields an estimate of the bulk soil radar velocity from the surface down to the isolated object or pipe. The depth to an isolated object or pipe does not need to be known in order to use this method. However, the visual fitting of the best curve to a reflection hyperbola is somewhat subjective and can lead to inaccuracies in velocity determination.

Another technique for estimating velocity uses the GPR groundwave. Groundwaves travel in the shallow subsurface (0 to ~30 cm) directly between the transmitting and receiving antennas. By noting the antenna separation and measuring the time needed for energy to travel between antennas, the velocity can be calculated. Groundwaves do not require a reflective interface and so can be applied in many soil environments. Because water content is commonly influenced by soil texture, groundwave measurements have also been used to map variations in soil texture at the field scale (Grote et al., 2003). Some researchers (van Overmeeren et al., 1997; Galagedara et al., 2005; Grote et al., 2010) have also found that the groundwave sampling depth is frequency dependent. Multi-frequency groundwave data could therefore be used to map the shallow, three-dimensional distribution of water content.

In addition to reflection hyperbola and GPR groundwave, a third GPR technique for estimating water content in soil uses air-launched GPR to obtain reflections from the soil surface. In this technique, the magnitude of the reflection from the ground surface is used to measure the dielectric permittivity. Air-launched data can be acquired and processed quickly. However, the technique has a sampling depth of less than 5 cm and the accuracy of the data is greatly diminished by vegetation, uneven soil surfaces, and vertical variations in water content. As a result, this technique has limited applications (Serbin and Or, 2003).

Electromagnetic Induction (EMI)

Electromagnetic induction methods use ground conductivity meters (GCM). These meters consist of a transmitter coil and either a single receiver coil or multiple receiver coils that are spaced at prescribed distances. Ground conductivity meters generate alternating electrical currents that are passed through the transmitter coil. These alternating electrical currents generate a time-varying, primary electromagnetic field. This primary field induces eddy currents to flow through the soil and thereby generate a secondary electromagnetic field. The amplitude and phase of the primary and secondary electromagnetic fields are measured by the receiver coil(s). Under conditions known as “operating at low induction numbers” (McNeill, 1980), the secondary field is proportional to the ground current and is used to calculate the “apparent” or “bulk” electrical conductivity (EC_a) of the soil, which is commonly expressed in units of millisiemens per meter (mS/m).

Apparent electrical conductivity is a depth-weighted average measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in EC_a are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is principally affected by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, water content, and the temperature and phase of the soil water (McNeill, 1980). Apparent electrical conductivity increases with increases in concentration of soluble salts, content of water or clay, and temperature (McNeill, 1980). Although EMI has been principally used to map variations in EC_a, GCMs have also been used to map variations in magnetic susceptibility—a property useful in delineating hydric soils and differences in some lithologies (Allred et al., 2010).

Modern GCMs are well suited to soil studies. Each GCM is fairly lightweight and can be operated in pedestrian or mobile modes (fig. 6-6). Because EMI does not require direct contact with the ground, data collection is relatively easy, rapid, and inexpensive. EMI therefore allows a larger number of measurements than traditional soil survey tools and more comprehensive coverage of sites. Electromagnetic induction has been used in order 1, 2, and 3 soil surveys to indirectly measure the spatial and temporal variability of soil properties. Examples include salinity, texture, cation-exchange capacity, ionic composition, $CaCO_3$ content, moisture content, organic carbon content, plant-available nutrients, pH, bulk density, and structure (Doolittle and Brevik, 2014).

The effectiveness of EMI depends on the degree to which differences in EC_a correspond to differences in the property under investigation. In general, stronger correlations are obtained where large differences in measured soil property and EC_a occur and other soil properties that affect EC_a remain relatively invariable. Differences can be horizontal, vertical, or both. Weaker correlations and lower predictive accuracies occur where the measured soil property and EC_a display low variability in relation to other interacting and more variable soil properties that affect EC_a. EC_a mapping is recognized as one of the most valuable methods in agriculture for measuring the spatial variability of soil properties at field and landscape scales (Corwin, 2008; Lück et al., 2009).

The depth of investigation (DOI) for EC_a measurements made with GCM is generally taken as the depth of 70 percent cumulative response. The DOI is dependent on the conductivity of the soil and the frequency, dipole orientation, and intercoil spacing of the GCM. For the GCMs most commonly used in soil investigations, the DOI can range from about 30 to 300 cm. DOIs from 3 to 60 m are possible with other commercially available GCMs.

Interpretations are commonly based on the identification of spatial patterns within EMI data sets. EMI was initially used to assess soil salinity, but its use has expanded to include mapping soil types; characterizing soil water content and flow patterns; assessing variations in soil texture, compaction, and organic matter content; and determining the depth to subsurface horizons, stratigraphic layers, or bedrock surfaces. Electromagnetic induction has also been used to assess differences in lithology and mineralogy, pH, field-scale leaching rates of solutes, herbicide partition coefficients, cation-exchange capacity, available nitrogen, and exchangeable Ca, Mg, and $CaCO_3$ (Doolittle and Brevik, 2014).

Figure 6-6

Three of the commercially available ground conductivity meters used in soil investigations. Each has its own strengths and weaknesses. Pedestrian (left images) or mobile (right images) surveys can be conducted with each.

Advantages of EMI include its noninvasiveness, fast operating speed, and continuous recording of georeferenced data. The large amounts of georeferenced data that can be rapidly and inexpensively collected with EMI provide more complete characterization of the variability in soil properties at intermediate scales than traditional point-sampling methods. Electromagnetic induction does have limitations: results are indirect, semi-quantitative, and site specific and vary depending on the complexity of the interactions that occur among multiple and varying soil properties. In addition, sferics (magnetic impulses from lightning) and nearby power sources and metal objects can interfere with and degrade the quality of EMI measurements. Limited ground-truth information and knowledge of the soils and the sources of EC_a variation are required to properly interpret data.

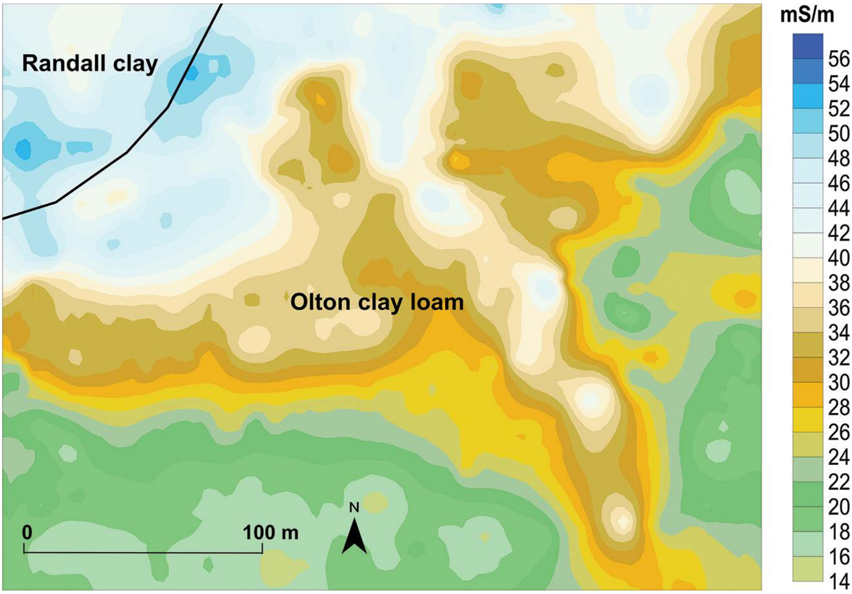
Examples of EMI Use in Soil Survey

Figure 6-7 shows the spatial variability of EC_a across a 7.7-ha range site that includes a portion of a dried-up playa bed in northern Texas. The very deep, poorly drained Randall soils (very-fine, smectitic, thermic Ustic Epiaquerts) formed in clayey lacustrine sediments on the playa floor. The very deep, well drained Olton soils (fine, mixed, superactive, thermic Aridic Paleustolls) formed in loamy, calcareous, eolian sediments on the slopes that surround the playa. At this site, variations in EC_a are principally associated with differences in soil moisture and clay content. Areas of higher EC_a (> 36 mS/m) were associated with the finer textured (> 50% clay), more imperfectly drained Randall soils.

On the EC_a map in figure 6-7, soil variability and the transition from one soil type to another are well expressed. The soil map unit boundary line was imported from Web Soil Survey (Soil Survey Staff, 2015). This boundary has a fixed width and cannot accurately portray the spatial rate of change or the complex spatial variability of soils and soil properties along the transition between playa and upland. As evident on this map, spatial EC_a data can improve the placement of the soil boundary line and the representation of soil variability.

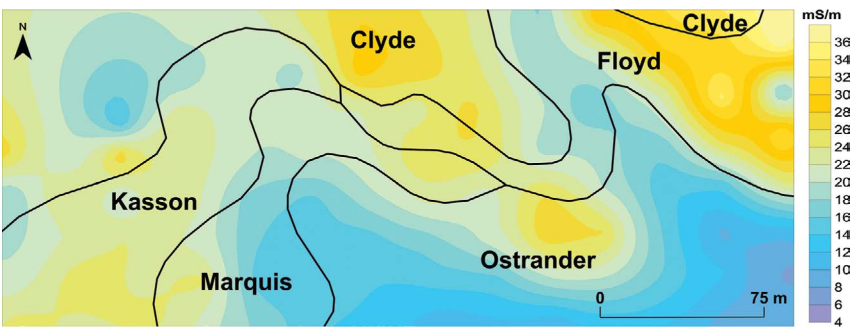
Figure 6-8 is an EC_a map of a 4.5-ha pasture in northeastern Iowa. Across this field, the surface slopes down to the north and northwest. The highest elevation is in the southeast corner of the field. The soil boundary lines were imported from the Web Soil Survey (Soil Survey Staff, 2015). In figure 6-8, the names of the dominant soil for each consociation are shown. These very deep soils all formed in loamy sediments overlying loamy till but belong to different soil drainage classes. Ostrander soils (fine-loamy, mixed, superactive, mesic Typic Hapludolls) are well drained; Kasson soils (fine-loamy, mixed, superactive, mesic Oxyaquic Hapludalfs) and Marquis soils (fine-loamy, mixed, superactive, mesic Oxyaquic Hapludolls) are moderately well drained; Floyd soils (fine-loamy, mixed, superactive, mesic Aquic Pachic Hapludolls) are somewhat poorly drained; and Clyde soils (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) are poorly and very poorly drained.

Figure 6-7



Spatial variations in EC_a within the upper 150 cm of the soil profiles at a site in northern Texas. This information was used to improve the placement of boundary lines and the characterization of soils. The map unit names and the soil boundary line were imported from the Web Soil Survey.

Figure 6-8



Spatial variations in EC_a within the upper 150 cm of five soils in northern Iowa. These variations are attributed principally to differences in soil drainage class and moisture content. Soil names and boundary lines were imported from the Web Soil Survey.

The complex spatial patterns evident on the high-intensity EC_a map in figure 6-8 principally reflect differences in soil drainage class and moisture content. In the northern portion of the field, areas of high conductivity (> 24 mS/m) closely mimic the distribution of the wetter, more imperfectly drained Clyde and Floyd soils. Areas of lower EC_a (< 20 mS/m) correspond with the higher-lying, better drained Ostrander soils, which are on convex surfaces that dominate the southeastern portion of the field. Areas of higher conductivity that extend northwest to southeast are associated with draws situated between higher-lying ridgelines. Apparent conductivity maps, such as figure 6-8, help reveal the complexity of soil-landscape architectures and their impact on subsurface flow and soil moisture patterns at field scales.

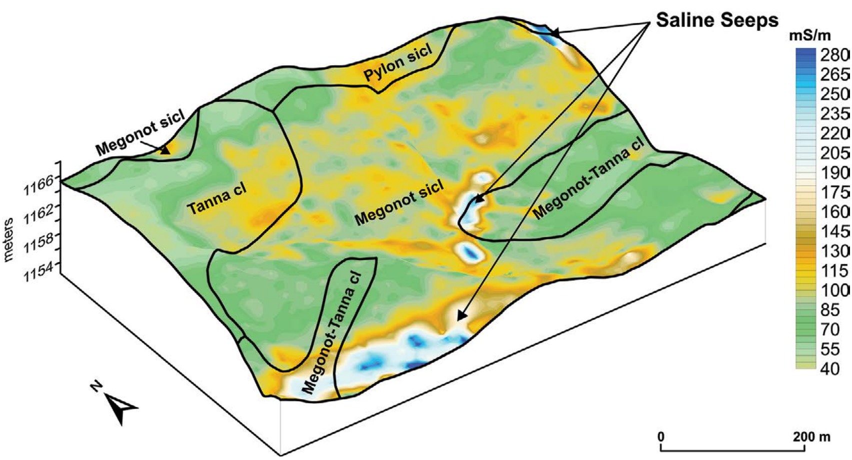
Figure 6-9 shows the spatial variability of EC_a within the upper 150 cm of a soil that contains saline seeps. The 64.7-ha field is in north-central Montana. The soil map unit boundary lines were imported from the Web Soil Survey (Soil Survey Staff, 2015). The soils are Megonot (fine, smectitic, frigid Torrertic Haplustepts), Pylon (fine, smectitic, frigid Torrertic Haplustalfs), and Tanna (fine, smectitic, frigid Aridic Argiustolls). These moderately deep, well drained soils formed in residuum weathered from semi-consolidated shale and siltstone. The presence of saline seeps is largely controlled by surface geology, above-normal periods of precipitation, and farming practices that help water to move beyond the root zone. As excess water moves through the soil, it dissolves water-soluble minerals. When an impermeable layer is encountered, the downward flow of water is restricted and redirected laterally along the restricting layer into lower-lying slope positions. Saline seeps develop wherever the saline ground water comes within about 1.5 m of the surface (Daniels, 1987).

In figure 6-9, the saline seeps are identified by their high EC_a (> 170 mS/m). These seeps are arranged in a discontinuous, sinuous pattern. They meander across the field from the southwest to the northeast along the base of slopes. This plot also shows lines of moderate EC_a that extend upslope away from the seeps. The areas of high EC_a represent discharge areas for subsurface flow where dissolved salts concentrate when water is lost by evapotranspiration. Recharge areas for the subsurface flow are located upslope from the saline seeps (to the west and north) and have relatively low EC_a (< 85 mS/m).

Electrical Resistivity (ER)

Soil electrical resistivity represents the capacity of soil materials to resist the flow of electrical current. Methods that calculate the apparent

Figure 6-9



Spatial distribution of EC_a across a cultivated field in north-central Montana. Spatial EC_a patterns provide inferences about flow of subsurface water and soluble salts across this landscape and about the distribution of recharge, discharge, and flow-through areas that contribute to the development of saline seeps. Soil names, surface textures, and boundary lines were imported from the Web Soil Survey.

electrical resistivity use Ohm's law and the measured injected current, the measured potential difference, and a geometric factor. The geometric factor is a function of the electrode spacing or configuration (Samouëlian et al., 2005). Apparent resistivity is commonly expressed in units of ohm-meters (Ωm). The apparent resistivity is a complex function of the composition and arrangement of solid soil constituents, porosity, pore-water saturation, pore-water conductivity, and temperature (Samouëlian et al., 2005). Electrical resistivity methods can be divided into those that inject currents into the ground through direct coupling and those that inject through capacitively induced coupling. Typically, both types of methods measure the apparent electrical resistivity, which is subsequently converted to its inverse, the apparent electrical conductivity of the soil.

Direct-Coupling ER

The traditional direct-coupling electrical resistivity method, also known as the galvanic source method, injects electrical current into the soil using an array of electrodes that are in contact with the ground. In a common four-electrode array, an electrical current is applied between two "current" electrodes and the voltage (the electric potential difference) is measured between two "potential" electrodes. For field surveys, current and potential electrodes are maintained at a fixed distance from each other. The array is moved along a survey line to successive measurement points. Horizontal and vertical resolution, depth of investigation, and signal-to-noise ratio vary with the configuration of the electrode array (Samouëlian et al., 2005). The depth of investigation and volume of soil materials measured increase with increasing electrode spacing. Conversely, resolution decreases with increasing electrode spacing. Depending on the relative positioning of the potential and current electrodes, several different array configurations are possible. The three most common configurations are the Schlumberger, Wenner, and dipole-dipole (Allred et al., 2008b). The Wenner array is more sensitive to mapping lateral changes in electrical resistivity. The Schlumberger and dipole-dipole arrays are often preferred for vertical soundings that measure variations in apparent resistivity with depth (Allred et al., 2008b; Samouëlian et al., 2005).

In many investigations, ER data are inverted. Inversion is an iterative process that results in a 2D or 3D model of the subsurface that best fits the acquired data. However, models constructed from inverted data provide nonunique solutions. Models are nonunique because, based on the constraints applied during the inversion process, several solutions or representations of the same data set are possible.

Apparent electrical resistivity has been used in order 1, 2, and 3 soil surveys to indirectly measure and characterize variations in soil structure and physico-chemical properties, detect preferential flow paths, and monitor temporal changes in soil water distributions. As noted by Samouëlian et al. (2005), electrical resistivity allows the delineation of soil types and, when performed repeatedly over time, provides information on soil functioning.

Standard ER surveys, which require the repetitive insertion and removal of electrodes from the soil, are relatively labor-intensive and time-consuming. To reduce survey time, computer-controlled, multi-electrode systems with tens to hundreds of electrodes have been developed (Allred et al., 2008b). These systems, however, have had limited use in soil studies.

Highly mobile, continuously recording, towed-array ER systems have been developed to expedite fieldwork and facilitate the collection of spatially dense data sets at field scales. In the United States, towed electrode-array ER systems have been used in precision agriculture and soil research (fig. 6-10). A commonly used system has six coulter-electrodes (two current and four potential electrodes) with nonadjustable spacing (Veris Technologies, 2016). It is configured in a modified Wenner array (Sudduth et al., 2005) and programed to simultaneously map EC_a

over two soil depth intervals (i.e., 0 to 30 cm and 0 to 90 cm) (Lund et al., 2000). Other systems use a single adjustable array to map EC_a within the top 45 to 90 cm of the soil profile. Both systems are preprogrammed and do not need calibration. In addition, unlike EMI sensors, measurements are not affected by sferics (electromagnetic pulses caused by atmospheric phenomena) or by nearby metallic objects, utility wires, or engines. However, towed-electrode arrays are invasive so their field use is commonly restricted by plant growth and cover and soil wetness. As soil contact must be maintained at all times during mapping, these systems should be operated neither on frozen or rocky soils nor in some bedded or furrowed cultivated fields.

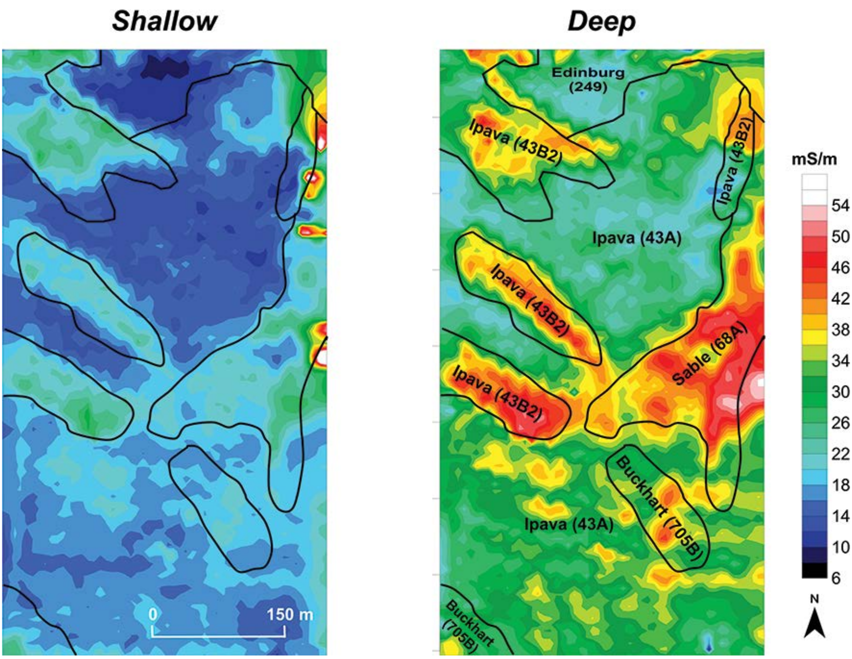
Figure 6-10

A towed electrode-array (six coulter-electrodes) soil EC_a mapping system behind a utility vehicle in a field of corn stubble.

Example of Direct-Coupling ER Use in Soil Survey

Figure 6-11 shows the results of a high-intensity survey conducted across a 32.4-ha field in western Illinois. Soil names, map unit symbols, and boundary lines from a high-intensity soil survey are shown on the plot of the deep (0 to 90 cm) data (image on right). Only the boundary lines are shown on the plot of the shallow (0 to 30 cm) data (image on left). The soils are very deep Mollisols that formed in thick loess deposits and belong to the fine-silty and fine particle-size classes. Although they belong to different particle-size classes, the soils do not vary appreciably in clay content. They range from poorly drained Aquolls to somewhat poorly drained and moderately well drained Udolls. Major soils identified within the study site are Ipava, Buckhart, Edinburg, and Sable soils. The somewhat poorly drained Ipava soils (fine, smectitic, mesic Aquic Argiudolls) and the moderately well drained Buckhart soils (fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) are in upland areas. The poorly drained Sable (fine-silty, mixed, superactive, mesic Typic Endoaquolls) and Edinburg soils (fine, smectitic, mesic Vertic Argiaquolls) are along intermittent drainageways and in broad summit areas, respectively.

Figure 6-11



Maps of apparent conductivity prepared from shallow and deep data collected in west-central Illinois.

In figure 6-11, the EC_a is noticeably lower in the shallow (0 to 30 cm) map than in the deep (0 to 90 cm) map. This is due to the increase in clay and water contents in deeper horizons. For the deep measurements, areas with lower EC_a represent better drained, higher-lying areas of Ipava and Buckhart soils. Higher EC_a values were measured in the more sloping and eroded areas of Ipava soils (43B2) where the argillic horizon is shallower and seepage was observed. Lower-lying areas of Sable soils are wetter and have a higher EC_a. In the southern portion of the field, on the deep map, faint patterns of three parallel, essentially east-west-trending terraces can be identified by their higher EC_a.

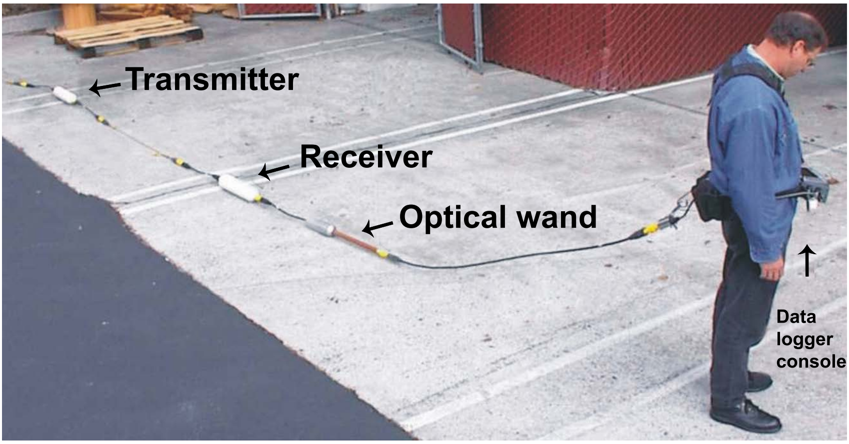
Capacitively Induced Coupling

Capacitively induced coupling resistivity (CCR) systems use capacitive coupling rather than galvanic contact to introduce electric current into the ground. They measure voltage at the surface in order to determine apparent soil electrical resistivity. The capacitive coupling uses coaxial cables to form a large capacitor. The metal shield of the coaxial cable is one of the capacitor plates and the soil surface is the other. The outer insulation of the coaxial cable acts as the dielectric material separating the two plates. The system transmitter applies an alternating current (AC) to the coaxial cable side of the capacitor, which in turn generates AC in the soil on the other side of the capacitor. With regard to the receiver, a similar phenomenon occurs, except in reverse. The AC in the soil charges the receiver coaxial cable capacitor, and the measured capacitance is then used to determine the potential difference (voltage) generated by the flow of electric current within the soil.

One of the more common CCR systems has two coaxial cables attached to the transmitter, one on each side, to form a current dipole, and it has two coaxial cables attached to the receiver, one on each side, to form a potential dipole (Geometrics, 2001). The depth of investigation for the system is 0.1 to 20 m, depending on dipole cable and tow-link length. This set-up, along with some initial data processing, allows this CCR system (fig. 6-12) to mimic a conventional galvanic contact dipole-dipole electrode array. A conventional array consists of one pair of current electrodes (current dipole) and one pair of potential electrodes (potential dipole). By increasing the distance between the receiver and transmitter dipoles, the depth of investigation and volume of soil measured are increased (Walker and Houser, 2002). Inverse modeling methods can be employed to produce depth profiles of electrical conductivity (fig. 6-13) if CCR data are collected along a transect line using several different spacing distances between transmitter and receiver dipoles.

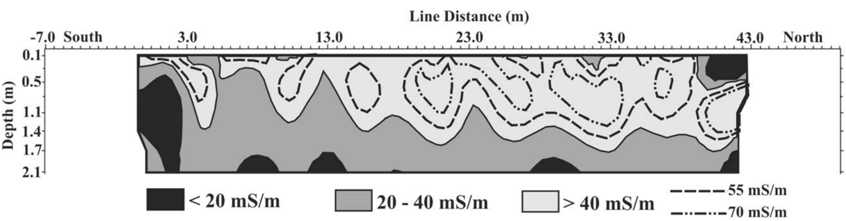
Capacitively induced coupling resistivity systems are rarely used in soil studies. In the field, the lines are easily snared on obstacles and broken off (Gebbers et al., 2009). CCR systems work exceedingly well in high resistivity soils, where it is often difficult to transfer sufficient current into the ground with towed-electrode array systems. In highly conductive soils, however, these systems provide little signal penetration and the resulting data are noisy (Gebbers et al., 2009).

Figure 6-12



A common capacitively induced coupling resistivity system. (Photo courtesy of Geometrics, Inc.)

Figure 6-13



A soil electrical conductivity depth profile from an agricultural test plot at the Ohio State University in Columbus, Ohio. The data for this profile were collected using spacing distances of 0.625 m, 1.25 m, 2.5 m, and 5 m between receiver and transmitter dipoles. To generate the soil electrical conductivity profile shown, data were input to a two-dimensional, least-squares optimization, inverse computer modeling program developed by Loke (2014).

Less Common Proximal Sensing Methods

The proximal sensing methods that are less commonly used by the National Cooperative Soil Survey include magnetometry, magnetic susceptibility, portable X-ray fluorescence, time domain reflectometry, optical reflectance, gamma-ray spectroscopy, mechanical interactions, ion-selective potentiometry, and seismic.

Magnetometry (MT)

Magnetometry is a passive remote sensing method that records the magnitude of the Earth's local magnetic field. Its sensors, called magnetometers, may be placed on the ground surface, in the air, in satellites, or in boreholes beneath the surface of the Earth. For measurements in agricultural fields, magnetometers are typically positioned within a couple of meters of the ground surface. Gradiometers, which are better adapted to emphasize magnetic field anomalies from shallow sources, are set up with two magnetometers mounted a short distance (< 1 m) apart. This arrangement allows the magnetic field gradient between them to be measured (fig. 6-14). Gradiometers have the added advantage of eliminating the need to make corrections for diurnal fluctuations in the magnetic field. Magnetic surveys using gradiometers have successfully found disturbances (e.g., backfilled trenches and excavated areas) in

Figure 6-14

Magnetic surveying with a cesium vapor gradiometer (Geometrics, 2016) integrated with a global positioning system receiver (Trimble, 2016).

iron-rich soils (Rogers et al., 2005). This suggests the potential use of this technology to identify the extent and location of some anthropogenic soils, particularly in order 1 soil survey applications.

Magnetic Susceptibility (MS)

Magnetic susceptibility is a measure of the degree to which a material can be magnetized when subjected to an applied magnetic field. The magnetic susceptibility of soil depends on the concentration, size, and shape of strongly magnetic minerals as well as the method of measurement (Mullins, 1977). Strongly magnetic minerals include ferromagnetic minerals, such as magnetite, maghemite, titanomagnetite, and pyrrhotite. Sources of MS can be lithogenic, pedogenic, or anthropogenic (Grimley et al., 2004). In soils, MS is influenced by differences in parent material, soil age, texture, mixing, firing, weathering, additions to the soil (commonly anthropogenic), pH, organic matter content, and soil moisture content (Maier et al., 2006; Grimley et al., 2004; Mullins, 1977).

Handheld susceptibility meters allow MS measurement across soil surfaces, down small-diameter holes, and on exposed sections (e.g., Bartington, 2016). These single-coil sensors require direct contact with the soil, and their depth of investigation is related to the diameter of the coil. The effective penetration depth of most handheld susceptibility sensors is limited to about 1 to 10 cm. Borehole sensors, however, can document vertical contrasts in susceptibility to depths as great as 20 m (Dalan, 2006). Unlike GPR, EMI, and ER, magnetic susceptibility surveys are not significantly affected by variations in soil moisture content. Because the volumes that are measured by MS sensors are small, high spatial resolution can be achieved. However, the accuracy of handheld, single-coil MS sensors is diminished by thermal drift and in areas that have rough, rocky surfaces or thick vegetation.

Magnetic susceptibility can also be measured with ground conductivity meters (GCM). The inphase component of the secondary electromagnetic field in a GCM is considered proportional to, and has been used to map, variations in magnetic susceptibility. However, the inphase response of an EMI sensor is more restricted by depth than the quadrature phase response (apparent conductivity). The inphase response of a commonly used meter measures only the top 50 cm of soil (Dalan, 2006). Interpretations of magnetic susceptibility from EMI data are also challenging. Variations are caused by differences in instrument configuration, instrument height and orientation, surface topography and roughness, depth to target, and changes in the sign (±) of the response in relation to target depth (Shamatava et al., 2007; Tabbagh, 1986). Other drawbacks of EMI sensors include instrument drift and the use of an arbitrary zero level.

Results of MS surveys are displayed as individual profiles or contour plots. Typically, field measurements of MS are reported in dimensionless volume units, e.g., 10^{-5} (SI) (Mullins, 1977).

Where sufficient contrast in magnetic properties exists, MS has been associated with pedogenesis (Fine et al., 1989), gleying (Vadyunina and Babanin, 1972), slope position (De Jong et al., 2000), soil drainage class and texture (Grimley et al., 2004), human disturbances (Dalan and Banerjee, 1996), and industrial pollutants (Fialová et al., 2006; Magiera et al., 2006). Where the concentration of magnetic minerals is sufficiently high, MS has been used to delineate boundaries of hydric soils (Lobred and Simms, 2009; Zwanka et al., 2007; Grimley et al., 2004; Arruda and Grimley, 2002; Grimley and Vepraskas, 2000) and to differentiate soil types (Hanesch and Scholger, 2005; Dearing et al., 1996; Vadyunina and Smirnov, 1978). Magnetic susceptibility is most applicable to some order 1 soil surveys.

Portable X-Ray Fluorescence (P-XRF)

Portable X-ray fluorescence spectrometers use high-energy incident X-ray photons to forcibly eject electrons from the inner shell of atoms. The resulting electron holes cause instability, which causes electrons from the outer shell to drop into the inner shell and fill the voids. This process results in the emission of X-ray energy, which is referred to as X-ray fluorescence. Because the energy emitted as fluorescence is element specific, different elements can be identified and quantified (Weindorf et al., 2012a). A comprehensive discussion of P-XRF is provided by Kalnicky and Singhvi (2001). Soil samples and exposed surfaces can be readily scanned with P-XRF spectrometers (fig. 6-15).

X-ray fluorescence has been principally used to assess metals in contaminated soils (Dao et al., 2012; Schwarz et al., 2012; Weindorf et al., 2012b; Kalnicky and Singhvi, 2001). Weindorf et al. (2012a) used P-XRF to improve descriptions of soil morphology and differentiate soil horizons based on the concentration of different metals. In gypsiferous soils of west Texas, Weindorf et al. (2009) used P-XRF to quantify the calcium content and determine the percent of gypsum. Beaudette et al. (2009) conducted P-XRF surveys in two watersheds, one formed over metavolcanic rocks and the other over granite. They used the resulting geochemical data to infer differences in soil development weathering indices, mineralogy, and geologic signatures. Doolittle et al. (2013) used EMI and P-XRF data to characterize differences in the mineralogy and lithologies of serpentinite- and non-serpentinite-derived soils in the Northern Piedmont of Pennsylvania. In soil survey, P-XRF is primarily applicable to point data documentation.

Figure 6-15

A portable XRF spectrometer, which can be attached to a monitoring bench in an office to scan collected samples (left) or can be used in the field to scan exposed faces of soil pits or surfaces (right).

Time Domain Reflectometry (TDR)

Time domain reflectometry (TDR) measures soil water content and, with some sensors, electrical conductivity. The use of TDR in soil science was pioneered by Topp, Davis, and Annan (1980). TDR infers water content and electrical conductivity from the measured dielectric permittivity and signal attenuation, respectively (Jones et al., 2002).

With TDR, a waveguide, or probe, of known length is inserted into the soil and the travel time for a generated electromagnetic pulse to traverse this length is measured. Using empirical (Topp et al., 1980; equation 1) or dielectric mixing models, the travel time is converted into a velocity of pulse propagation. The velocity of propagation is used to determine the soil's bulk dielectric permittivity, which is used to infer the volumetric water content. The dielectric permittivity is directly related to soil volumetric water content.

According to Jones et al. (2002), some of the advantages of TDR are: (1) accurate estimations of soil volumetric water content (to within ± 2% without soil-specific calibration), (2) minimal calibration requirements in most soils, (3) absence of radiation hazards that are associated with neutron probe or gamma-attenuation techniques, (4) excellent spatial and temporal resolution, and (5) ease of measurements. Some of the disadvantages of TDR are: (1) measurement errors can occur if there are gaps between the soil and probe, (2) TDR is limited in highly saline and frozen soils (Ferrara and Flore, 2003), (3) special calibrations are required in soils that have a high content of clay or organic matter content, and (4) probes are difficult to insert in some soils.

A variety of TDR sensors are available for determining water content in soil. Depending on the length of the waveguide, TDR sensors can provide bulk soil moisture measurements over different soil depths. In soil survey, time domain reflectometry is primarily applicable to point-data documentation.

Optical Reflectance (UV, vis-NIR, mid-IR)

Optical sensors are used to determine the soil's ability to reflect light in different parts of the electromagnetic spectrum. Proximal optical sensors are fundamentally the same as remote sensing systems. The advantage of proximal sensors is that they can be applied at the surface and below ground (fig. 6-16). In soil survey, optical reflectance is applicable to point data documentation. It can be used for on-the-go measurements during different soil survey practices. In addition, both near and mid infrared diffuse reflectance spectroscopy are being used in the laboratory for rapid determination of some soil properties. Optical sensing systems cover the ultraviolet (100–400 nm), visible (400–750 nm), near infrared (750–2,500 nm), or mid infrared (2,500–25,000 nm) wavelengths or a combination of these wavelengths. Typically, instruments used for soil measurements include their own light source (e.g., a light bulb or light-emitting diode). Photodiodes or array detectors are used to estimate the intensity of reflected light and relate this measure to the light reflected from a given set of standards. Both source and reflected light can be transmitted through the air, via fiber optics, or when feasible, through a contact window fabricated from highly resistive material, such as sapphire or quartz.

Measurements obtained using optical sensors can be related to a number of soil attributes, such as soil mineral composition, clay content, soil color, moisture, organic carbon content, pH, and cation-exchange capacity (Christy, 2008; Viscarra Rossel et al., 2009; Mouazen et al., 2010). Measurements can be direct or indirect. For direct measurements, relationships are based on a physical phenomenon that affects light reflectance in a specific part of the spectrum (e.g., soil mineralogy or

Figure 6-16

A probe equipped with insertion load sensors and two spectrometers, which cover visible and near infrared parts of the spectrum as well as electrical conductivity.

water content is predicted using water absorption bands). For indirect measurements, relationships are deterministic for a finite domain and the combined effects of several soil attributes can be related to a given soil characteristic (e.g., soil organic matter). Sensor calibration strategies range from a simple linear regression to multivariate methods, chemometrics, and data mining (Viscarra Rossel et al., 2006). Although some of these models may be applied to large geographic areas, most are currently associated with a specific range of soils.

Ultraviolet (UV) radiation has been used in combination with visible or infrared spectra (e.g., Islam et al., 2003). Ultraviolet and visible spectra have been used to characterize inorganic minerals, such as iron oxides (Schwertmann and Taylor, 1989). An extensive range of reports is available on the use of visible near infrared (vis-NIR) and mid infrared (mid-IR) spectra for soil analysis. Both laboratory conditions and proximal soil sensing have been investigated. The mid-IR contains more information on soil mineral and organic composition than the vis-NIR, and its multivariate calibrations are generally more robust. The mid-IR has these advantages because fundamental molecular vibrations of soil components occur in the mid-IR while only their overtones and combinations are detected in the vis-NIR. Thus, soil vis-NIR spectra display fewer and much broader absorption features compared to mid-IR spectra.

Gamma-Ray Spectroscopy

Gamma rays contain a very large amount of energy and are the most penetrating radiation from natural or artificial sources. Gamma-ray spectrometers measure the distribution of the intensity of gamma (γ) radiation versus the energy of each photon. Sensors may be either active or passive. Active γ-ray sensors use a radioactive source (e.g., cesium-137) to emit photons of energy that can then be detected using a γ-ray spectrometer (e.g., Wang et al., 1975). Passive γ-ray sensors measure the energy of photons emitted from naturally occurring radioactive isotopes of the element from which they originate (e.g., Viscarra Rossel et al., 2007). Soil elemental isotopes can be mapped by a γ-ray sensor on a vehicle (fig. 6-17). Data interpretation may include analysis of measures related to the isotopes of potassium, thorium, and uranium or the total count. Such mapping can be a useful tool for predicting soil properties in different soil landscapes. A significant amount of preprocessing, however, is commonly required to reveal relationships between the γ-ray spectra and the soil data (Viscarra Rossel et al., 2007). In soil survey, gamma-ray spectroscopy is primarily applicable to order 1 surveys (and possibly some order 2 or 3) as well as to point-based measurements.

Figure 6-17

A vehicle-mounted passive gamma-ray sensor.

Inelastic neutron scattering (INS) spectroscopy (Schrader and Stinner, 1961) relies on the detection of γ-rays that are emitted following the capture and reemission of fast neutrons as a sample is bombarded with neutrons from a pulsed neutron generator. The emitted γ-rays are characteristic of the excited nuclide, and the intensity of γ-rays is directly related to the elemental content of the sample. The detectors used are the same as those used in γ-ray spectroscopy. Wielopolski et al. (2008) proposed the use of INS spectroscopy for the measurement of carbon and other elements in soils.

Mechanical Interactions

Simple mechanical sensors can be used to estimate soil mechanical impedance (resistance). By nature, these soil strength sensors measure resistance to soil failure (Hemmat and Adamchuk, 2008). As a mechanical resistance sensor moves through the soil, it registers resistance forces arising from the cutting, breakage, and displacement of soil, as well as from the parasitic (frictional and adhesive) forces that develop at the interface between the sensor's surface and the surrounding soil. Normally, soil mechanical resistance is expressed in units of pressure and represents the ratio of the force required to penetrate the soil media and the frontal (normal to the direction of penetration) area of the tool engaged with the soil.

The first step toward soil mechanical resistance sensing is to map the total horizontal (draft) force and, in some cases, the total vertical force applied to a traditional fixed-depth implement engaged with the soil. Recorded measurements represent surrogate values affected by a variety of factors, including the type and shape of the tool working the soil, the speed and depth of the operation, and the surface conditions. In addition to vertically operated cone penetrometers, horizontal sensors have been designed to generate high-resolution maps of horizontal soil penetration resistance obtained at a specific depth. Multiple tips can be simultaneously deployed at different depths. Such an arrangement allows researchers to determine the spatial variability of soil mechanical resistance at any available depth as well as vertical variability in each location of the field.

To avoid the expense of adding direct load-sensing tips, a single-tip horizontal sensor can be actuated vertically in a way similar to a bulk soil strength sensor. In addition to using a tip-based method, the vertical distribution of soil mechanical resistance can be measured using an instrumented tine. This distribution is measured by sensing the direct load applied to the tine at discrete depths and/or by measuring the degree of bending using strain gauge technology (i.e., a cantilever beam approach). Maps of soil mechanical resistance corresponding to a 20–30 cm depth layer can reveal the appearance of old infrastructure, such as roads. Soil mechanical impedance changes with soil water content and bulk density. On-line soil moisture sensors (typically capacitance or near-infrared reflectance probes) have been used to separate these two soil attributes.

Acoustic and pneumatic sensors can be alternatives to mechanical sensors for the study of the interaction between soil and an agricultural implement. Acoustic sensors have been used to determine soil texture, bulk density, or both by measuring the change in the level of noise caused by the interaction of a tool with soil particles. Pneumatic sensors have been used for on-the-go sensing of air permeability in soil. The pressure required to force a given volume of air into the soil at a fixed depth was compared to several soil properties, such as soil structure and compaction. In soil survey, mechanical interactions are primarily applicable to order 1 surveys and point data documentation.

Ion-Selective Potentiometry

Ion-selective potentiometry sensor systems resemble a traditional wet-chemistry method to assess the content of certain chemical ions and compounds. They can provide the most important type of information needed for precision agriculture—soil nutrient availability and pH. The measurements are conducted using either an ion-selective electrode (ISE) or an ion-selective field effect transistor (ISFET). These sensors detect the activity of specific ions at the interface between sensitive membranes and the aquatic part of either a soil solution or a naturally moist sample. A common ISE system consists of a membrane that is sensitive to specific ions and a reference electrode. The difference in the potential between the sensitive membrane and the reference is measured and converted to the activity of specific ions in the tested solutions. The design of a combination ion-selective electrode allows both sensitive and reference parts to be assembled in one probe. Different electrode brands represent different designs of ion-selective membranes and reference junctions.

An ISFET integrates the ion-selectivity of an ISE with the small size and the robust nature of a field effect transistor. The current between two semiconductor electrodes (source and drain) is controlled by a gate electrode represented by an ion-selective membrane. As ions of interest affect the gate, their charge impacts the source-drain current, which provides an indication of ion activity. The main differences between an ISFET and an ISE are that an ISFET does not contain an internal solution and the ion selective membrane is affixed directly on the gate surface of the ISFET. ISFET technology is attractive because of its compact size and theoretically high signal-to-noise ratio, especially when used for the flow injection analysis (FIA) method. However, the range of commercially available ISFETs remains relatively narrow. The sensitive membrane in both ISE and ISFET is made of glass (H^+, Na^+), polyvinyl chloride (K^+, NO_3^-, Ca^{2+}, Mg^{2+}), or metal (H^+).

A range of approaches can be used to establish the interface between an ISE or ISFET and a soil solution. Some methods involve great detail; some are relatively simple. On one end of the range of possibilities is a complete sample preparation with a prescribed controlled ratio between soil particles and extracting solution. This method adds complexity to the measurement apparatus and often requires a longer sampling time and analysis cycle (Viscarra Rossel et al., 2005). On the other end is a direct, simple measurement (DSM) approach, which is relatively easy to implement (Adamchuk et al., 2005). The real-time chemical extraction of the ions mimics conventional soil analysis procedures. DSM-based measurements reveal specific ion content in a given soil state, which may not represent nutrient availability throughout the growing season. Because chemical processes in soil are frequently influenced by the physical composition of the soil, combining direct ion activity measurements with geophysical instruments (described earlier) can help predict conventional laboratory test values used to prescribe various soil amendments (fig. 6-18). In soil survey, ion-selective potentiometry is primarily applicable to order 1 surveys and point data documentation.

Figure 6-18

A sampling mechanism for a towed system that simultaneously maps soil pH and apparent electrical conductivity.

Seismic

Seismic waves are essentially elastic vibrations that propagate through soil and rock materials. Artificial energy sources can be used to introduce seismic waves into the ground for investigatations of subsurface conditions or features. Examples of energy types include explosive, impacting, vibratory, and acoustic. For seismic geophysical methods in which artificial energy is supplied, the seismic waves are timed as they travel through the subsurface from the energy source to the sensors, which are called geophones. Incoming seismic wave amplitudes, and hence energy, are also measured at the geophones. The energy source is ordinarily positioned on the surface or at a shallow depth, and the geophones are typically inserted at the ground surface. Data on the timed arrivals and amplitudes of the seismic waves measured by the geophones provide insight into belowground conditions or help to characterize and locate subsurface features.

Traditional seismic methods have rarely been used for agricultural purposes. However, laboratory studies employing 2 to 7 kHz acoustic-sourced seismic waves have shown that seismic wave velocities correlate significantly with soil compaction, soil porosity, and soil water content and that acoustic-sourced seismic wave absorption coefficients exhibit significant correlation with soil bulk density and soil water content (Oelze et al., 2002; Lu et al., 2004). In the Appalachian Highlands Physiographic Province of northwestern Virginia, Olson and Doolittle (1985) used seismic refraction to determine the elevation of the water table and depth to bedrock. They noted, however, that this geophysical method could not distinguish soil profile characteristics. Seismic tools are potentially applicable in order 1, 2, or 3 soil surveys.

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CHAPTER 7

Soil Survey Data Collection, Management, and Dissemination

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Introduction

During the course of a soil survey, a large amount of data, of various types and in various formats, is commonly collected or developed. These data include, but are not limited to, field notes, soil profile and landscape descriptions, drawings, laboratory data, photographs, descriptions of soil map units and map unit components, and, of course, the basic soil map.

Before a soil survey project begins, a decision must to be made as to what type of system is going to be used to collect, store, manage, and disseminate the information to be gathered and/or developed. For example, the data and information may be maintained and distributed as hard copy, in electronic form, or by some combination of the two. Deciding how to manage these data can be a daunting task, but it is a very important one.

First, a few questions need to be answered:

- What is the purpose of the soil survey?
- For whom is the information intended?
- Is the information to be publicly available to anyone that wants it, or is it to be kept within the organization that is conducting the soil survey?
- What types of products or output will need to be generated at the end of the project?
- In what format are the products to be made available—electronic or hard copy, or both?
- Do the end users of the information only need the summarized soil survey data, or will they also need access to the various pieces of point data collected at individual points on the landscape?

- Will the data and/or generated information be delivered via the Internet?
- What resources and expertise are available for maintaining and disseminating the data?

The answers to these and other questions will help determine what sort of system is needed.

To begin this discussion, a distinction needs to be made between "soil data" and a "soil information system." Soil data refers to the actual data that are collected or generated during the course of a soil survey. A soil information system includes not only the data, but also the various methods and/or systems used to collect, store, and manage the data and resulting interpretations and information and to disseminate them to end users.

A database can be defined as "a collection of information or data that is organized so that it can easily be accessed, managed, and updated." In its crudest of forms, a database can be a collection of paper copies maintained in a file cabinet or box. With a crude database, the ease of accessing, managing, and updating such data is limited. In electronic format, a database is generally a series of related data tables maintained within some database management software (DBMS) on a computer. The data can be both tabular data (which describes the characteristics and proportions of soils in the soil survey area) and spatial data (which contains the locations of soil map unit boundaries and site locations where specific soil samples and soil profile descriptions were collected and other field observations were made, as well as other thematic data layers).

If the decision is made to collect, store, and manage soil survey data in hard-copy format, the options for product delivery are minimal. If the decision is made to use an electronic format for data collection, storage, and management, then some type of electronic database(s) will be needed. There are numerous options for dissemination of data maintained in electronic format.

Automated Data Processing in Soil Survey

A powerful tool for handling accumulated soil survey data is automated data processing (ADP), which uses computers with word-processing, database, spreadsheet, statistical, geographic information system (GIS), and other specially designed software packages. ADP facilitates data collection and entry, data editing, and timely summaries, comparisons, and analyses of data that otherwise would be impractical or impossible to do. It enables frequent and inexpensive updating of long lists, such as lists of soil series for various geographic regions, in any order or sequence, and other output products. The summaries can provide information to guide important policy decisions. ADP can quickly perform routine and otherwise time-consuming computations. It allows for easy editing of descriptive materials, manuscripts, and narrative or tabular data and information.

In recent years, with the increased use of computers and the development of computer applications such as geographic information systems, more and more soil survey data are being delivered to end users in electronic or digital format (see chapter 5). Data also are, at least partially, being collected and recorded in electronic format in the field using a variety of tools (see chapter 6). Managing the data in digital format allows greater flexibility in data delivery. Products can be delivered to users in either hard-copy or electronic formats. The remainder of this chapter will be primarily devoted to the electronic format of soil data management and delivery.

Soil scientists need to know the fundamentals of ADP just as they need to know the fundamentals of chemistry, botany, geology, mathematics, economics, and other subjects that support the work of soil survey. Literature on the fundamentals of ADP is readily available. Automated data processing can be used for many soil survey tasks, but this does not mean that it should be used for all of them. Before any decision is made to use ADP, an objective study (systems analysis) is needed to determine what combination of equipment, personnel, and other factors will be the most useful and economical. The selection of any new system must take into account its compatibility with systems used by cooperating agencies to handle soil survey data and related physical and environmental data. Many combinations of computers, storage media, input-output devices, and communication facilities are possible.

Even after an ADP system has been designed and implemented, continuous study, testing, and improvement are needed. ADP technology is changing rapidly, and new equipment and new procedures are being developed constantly. As experience is gained, an existing system may need to be improved or replaced.

Automated data processing can manipulate data in many ways. Because most of the data are likely to be needed in different combinations, the basic use of ADP will probably be data storage and retrieval. For this use, precisely and consistently defined records need to be entered into some medium readable by computers and arranged in cataloged files.

These files of soil records are collectively referred to as a soil survey database.

Databases can be distributed between multiple locations or kept in a centralized system, depending on system requirements and facilities available. For example, in the early versions of the National Soil Information System (NASIS) used by the U.S. National Cooperative Soil Survey (NCSS), the database was divided (distributed) among 17 regional databases and each region managed soil survey data for their respective area. In later versions of NASIS, the database was merged (centralized) into a single national database. Currently, all users access the single database to create and manage the data for which they are responsible. A uniform coding system is essential for a consistent format of the data. It permits direct transfer and sharing of data and the use of computer programs to manipulate the data.

Databases can also be classified as transactional or publication. In *transactional databases*, ongoing edits and additions are made to the data. Generally, these databases are used only internally by members of the organization responsible for the database. NASIS is a transactional database. In *publication databases*, the database content is certified and made available to the public. The NCSS's Soil Data Mart is a publication database.

After soil information has been systematically entered into the database and the necessary equipment and operating instructions have been organized, the data are available for many kinds of operations. Computer programs (software) may need to be developed if they do not already exist. Software development is typically the most expensive and time-consuming aspect of data processing. A good data management system can reduce the amount of software needed. Important applications for soil survey include:

1. Answering questions. Examples are: What soils have certain sets of properties? What soils are mapped in specified localities? What soils will produce corn yields of more than 100 bushels per acre (approximately 6,700 kilograms per hectare) under a particular management system?
2. Performing statistical studies, particularly multiple correlations, for many purposes, including testing the numerical limits of values in Soil Taxonomy, determining what soil properties observable in the field correlate well with laboratory results, and determining what observable soil properties reliably indicate soil behavior.
3. Preparing summaries (e.g., summaries of interpretations by soil families, phases of soil families, subgroups, etc.; summaries

of the extent of the different soils in various geographic areas; summaries of the number and extent of soils having selected features such as a fragipan).

4. Arranging and printing out tabular material for soil survey manuscripts and other reports (see appendices). Text that is repeated in published surveys of a given State or region can be stored in finished form and reused as needed.
5. Storing and easily updating lists, such as the classification of soil series.
6. Generating interpretive maps and printing them on demand (see appendix 4). This application is becoming increasingly valuable for soil management and land use planning.

Users of ADP outputs must be aware of the importance of reliable and accurate original information. High-quality data must be entered at the outset. ADP cannot improve the quality of the data; only people can. However, it can be a valuable tool in finding data inconsistencies.

To store soil survey data in electronic format, one or more electronic databases are needed. These databases can become very complex, depending on how many soil attributes are to be recorded and stored and to what degree of resolution or frequency the data are to be collected.

Database design is an important consideration. A database can succeed or fail because of data consistency or the lack thereof. Standards need to be established to help ensure data consistency. It is important that the various tables and attributes or columns within the database be sufficiently defined so that there is no ambiguity as to what information is to be recorded in each table and/or column and in what format. This information describing the database, referred to as "metadata," needs to be made available to those individuals who are collecting and inputting the data into the database as well as to end users. The metadata can prevent the misunderstanding and misuse of the resulting soil data.

The electronic database can also employ a variety of data validation tools and rules to help ensure data integrity and data quality. For example, the database can allow only numeric values to be entered into a data field that is defined as requiring a numeric entry. The system can ensure that only values within a particular numeric range be entered (e.g., only values between 1 and 14 are allowed for pH). Choice lists can be developed to ensure that only approved terms are used for specified data elements and that data entries are consistently spelled.

The actual design and structure of the database is somewhat dependent on the type(s) of data being collected and/or needing to be stored and delivered to end users. It can also vary somewhat based on the database management software (DBMS) that will be used to manage the database.

Standard methodologies or protocols for data collection are needed to ensure that data collected from different locations, at different times, and by different people can be appropriately combined and summarized or evaluated as needed. For example, slope should be measured in the same way and clay content should be determined using the same procedures throughout the survey area.

Recording Data and Information—Field and Lab

Information gathered during the course of a soil survey is recorded in a variety of formats and content. In addition to the basic soil map, important forms of data include field notes, soil profile descriptions, laboratory analytical results, photographs, and drawings. These forms of information work together to ensure a quality survey. The data fall into three basics categories: point data, aggregated data, and spatial data. Each category is discussed in more detail in the following paragraphs.

Point Data

Point data are data that are collected, measured, or observed at a particular geographic location in the field. They generally record a single value for each attribute recorded about the soil map unit as a whole, or an individual soil map unit component, and the landscape in which it occurs. At a specific geographic location at a particular point in time, each attribute only has one value. Attributes may include slope, landform setting, depth to each soil horizon, pH or texture of each horizon, etc. Also included in point data are photographs taken at the sample location and sketches and drawings of the landscape and/or soil profile. Point data can be the results of direct field observations or measurements, analytical result of laboratory measurements from soil samples collected at the location, or the results from ongoing monitoring tools that collect data (such as soil temperature or soil moisture content) at regularly scheduled intervals.

Each piece of point data collected should include a reference to the soil map unit and/or soil map unit component that it represents. This is a part of the correlation process that takes place during the course of the soil survey project (see section titled "Correlation Steps" in chapter 4). The system developed to manage soil survey data needs to have the capability to manage all forms of point data that will be collected.

Soil Map Units vs. Soil Map Unit Components

When conducting a soil survey, the areas outlined on the soil map represent a segment of the natural landscape and are generally referred to as a map unit polygon or delineation. Each polygon is labeled with a map unit symbol that indicates which soil map unit it represents. It displays the extent of the soil map unit on the landscape and is defined as a collection of soil types that occur together in a regularly repeating pattern on the landscape. Each soil type within a particular soil map unit is referred to as a soil map unit component. The soil map unit component generally comprises approximately the same proportion of the map unit in each polygon of the soil map unit (e.g., for soil map unit "10," soil component A makes up 75% of the map unit, soil component B makes up 15%, and soil component C makes up 10%). Map units rarely are 100% composed of any particular soil type.

The level of detail of each map unit component is generally dependent upon the scale at which the soil map is being developed. Small-scale maps (e.g., those at 1:100,000) generally will have more broadly defined map unit components than larger scale maps (e.g., those at 1:12,000). For a more detailed discussion of soil map units and map unit components, see chapter 4.

Field Notes

Field notes include soil profile and landscape descriptions, descriptions of the relationship and interactions between soil components or map units, information on the behavior of the soils, and inferences about how the soils formed. The information delivered to end users to accompany the soil maps for each soil survey is developed based on the field notes. Field notes are used for preparing standard definitions and descriptions of soil series, soil map units, and map unit components and for correlating soils in the national program. They are as important as the map base on which soil map unit boundaries are plotted.

The best notes are recorded while field observations are fresh in the mind of the observer. For example, the description of a soil profile is recorded as it is being examined. Information from a conversation with a farmer is recorded during the conversation or immediately thereafter. Unless notes are recorded promptly, information may be lost. All field notes should be clearly identified. The survey area, date, location, and author are necessary for each note. Each note should be related to an identified soil map unit or map unit component. The source of the information, if not from direct observations, should also be identified.

To be available and useful, field notes must be organized and stored in a standardized manner. Electronic storage is a good solution. Notes that are handwritten in the field can later be scanned and stored in a computer database. Notes can also be recorded on handheld devices using word-processing or note-taking computer software in the field, and the resulting files stored in a standardized file folder structure on the computer.

Field notes must be understandable to all survey personnel. Shorthand notes need to be transcribed to standard terminology. Only common words and expressions, as found in a standard dictionary or technical reference, should be used.

The most important notes record the commonplace, such as the extensive kinds of soils and their properties, the common crops or vegetation, the performance of septic systems, etc. The tendency to record anything other than the commonplace should be avoided, because subsequent efforts to prepare a descriptive legend or make interpretations from such notes will be unsuccessful. However, in the early stages of a soil survey project, differentiating between the "commonplace" and "oddities" may be difficult. As work in the survey area progresses, what appear to be oddities in the beginning may later become commonplace as other parts of the survey area are mapped. Field notes should indicate how closely something represents the commonplace. Survey personnel must first learn to see and record the commonplace, then identify departures from the usual.

Field notes record observations as well as complete descriptions of pedons at specially selected sites. Notes that are made during daily mapping typically are not full descriptions. They may record only color, texture, and thickness of major horizons as seen in auger cores. This information is used to supplement detailed examinations. Notes of this kind are especially important for soils that are not well known and for soils of potential, but questionable, map units.

Field notes include information about the relationship of map units and map unit components to one another, to landforms, and to other natural features. The setting of a soil—its position in the landscape—is important. Landscape features strongly influence the distribution of soils. The properties and extent of the soil and the location of soil boundaries can be deduced from the landscape. The kind of landform or the part of the landform that a particular soil occupies and how the soil fits into the landscape should be described. Soil patterns and shapes of soil delineations are important in relation to large-scale soil management. Landscape identification is discussed in chapter 2.

The kinds and amounts of the various soil map unit components in each map unit, as well as their positions in the landscape, are noted and recorded during fieldwork. The soil map unit components are either identified by name or their contrasting properties are described. Although the kinds and amounts of map unit components vary somewhat from delineation to delineation, an experienced surveyor has little difficulty in maintaining an acceptable level of interpretive purity within a soil map unit. This is due to the fact that most contrasting map unit components (i.e., dissimilar soils and miscellaneous areas) occupy specific, easily recognized positions in the landscape. If a precise estimate of the taxonomic purity of a given delineation is needed, special sampling techniques, such as line transects or point intercept methods, are required.

Notes should be made on soil erosion in particular map units. They could include descriptions of eroded areas, degrees of erosion within and between soil phases, differences in variability among soils and landscape positions, extent of soil redistribution and deposition in map units, and effect of erosion on crop yields and management of the soil.

Soil behavior concerns the performance of a soil as it relates to vegetative productivity, susceptibility to erosion, and a particular land use (such as a foundation for houses or a waste disposal site). Notes on soil behavior, unlike those on the nature and properties of the soil, are obtained largely from the observations and experiences of local land users. Direct observations by field scientists and inferences made from them should be labeled as such.

Notes on behavior focus on the current and foreseeable uses of the important soils in an area. For example, if range is the primary land use in a survey area, information on range production along with plant community descriptions may be needed for all of the soils of the area. Notes on the performance of soils under irrigation, however, would probably be needed as well as where the soils are irrigated or may be irrigated in the future. Information on probable forest growth and plant community descriptions might be pertinent to the purposes of the survey even though it comes from the experience of only a few individuals or a few kinds of soils. An area with a rapidly expanding population needs data on the engineering performance of soils, such as how well the different soils would support houses, what kinds of subgrades would be required for streets and roads, and whether onsite waste disposal systems would function satisfactorily.

Valuable information about the performance of soils can be obtained from observations made in the field while surveying. Soil scientists can see poor crop growth on a wet soil or in an eroded area. They note the failure of a road subgrade or of an onsite waste disposal system in specific kinds of soil. However, data on yields and management practices for specific crops typically come from farm records or experimental fields. If records are not available, such as records that compare crop productivity between eroded and uneroded phases of a soil, special studies and data collection may be needed.

Information on forest growth or range production and the composition of a vegetative plant community also is commonly derived from observations made by others, but it can be supplemented by information recorded by the soil scientist. Most information on the engineering performance of a soil comes from people who work with structures and soil as a construction material. During fieldwork, a special effort should be made to obtain this kind of information from knowledgeable people.

The source of information about soil behavior is evaluated and recorded in the field notes. Inferences are to be clearly distinguished from observations of soil morphology, vegetation, landform, etc. Most notes about how soils formed, for example, are inferences. The condition of growing crops is observable, but statements about soil productivity based on such observations are inferences. That some soil material is nearly uniform silt loam and lacks coarse fragments is directly observed; the conclusion that the soil formed from loess is inferred. Theories formed on the basis of inference should not unduly influence the choice of observation sites or the properties to be observed.

Soil Profile Descriptions

Soil profile descriptions are basic data in all soil surveys (see chapter 3 for a detailed discussion). They provide a major part of the information required for correlation and classification of the soils of an area. They are essential for interpreting soils and for coordinating interpretations between soil survey areas. The soil descriptions and the soil map are the parts of a soil survey project that have the longest useful life.

Field descriptions of soil profiles range from partial descriptions of material removed by a spade or an auger to complete descriptions of pedons seen in three dimensions (from intersecting pits where horizontal layers were removed sequentially from the surface downward). Because most field descriptions of soil profiles are the former, care in making them is essential.

Field descriptions should include, but are not limited to:

- The date, time of day, and weather conditions;
- The name of the describer;
- The geographic location of the site;
- Observed external attributes of the pedon, such as landscape position, landform, and characteristics of slope;

- Inferred attributes of the pedon, such as origin of soil parent material and the annual sequence of soil water states;
- The plant cover or land use of the site;
- Observed internal properties of the pedon, such as horizon thickness, color, texture, structure, and consistence;
- Inferred genetic attributes of the pedon, such as horizon designations and parent material;
- Inferred soil drainage class; and
- The classification of the pedon in the lowest feasible taxonomic category.

The degree of detail that is recorded is somewhat dependent upon whether the description is intended to provide a complete soil profile description for comparisons with other pedons placed in the same taxonomic class or simply to determine the variation of a selected property within a taxon. One should keep in mind that the majority of the time and expense in collecting a description is in finding and getting to the sample site and exposing the soil profile. It is much more economical to get a complete description during the initial visit than to return to the site later. This is especially true when mapping remote areas.

The attributes of pedons, procedures for describing their internal properties, and standard terminology are described in chapter 3. When standard terms are not adequate to characterize all properties and attributes of a soil, common descriptive words are used.

Standard Forms and Terminology

Standard forms are useful for recording the observations and data required in a soil survey. They permit recording of information in a small space. A standard form used to record soil profile descriptions is illustrated in figure 7-1. This is merely an example; no standard form can cover all situations. Forms require modification as more is learned about soils and how to evaluate data. They can be automated to permit electronic recording of the information and limit the need for later data entry. Handheld computers can be programmed, following a standard format, to allow soil information to be entered by workers while in the field. The information can be uploaded later to a computer in the office or to a central database. The office computer can be used for storage of information, sorting, and printing out descriptions. Automated forms can avoid data transcription errors that occur during data entry, thereby improving data quality.

Figure 7-1

USDA-NRCS	**PEDON DESCRIPTION**	PEDON ID#:	2/2012

Series or Component Name:	**Map Unit Symbol:**	**Photo #:**	**Classification:**	**Soil Moist. Regime (Tax.):**

Describer(s):	**Date:**	**Weather:** **Temp.:** *Air:* *Soil:* *Depth:*	**Latitude:** ° ' " N **Geodetic Datum:** **Longitude:** ° ' " W	**Location:** Sec. T. R.

UTM: *Zone:* *mE:* *mN:*	**Topo Quad:**	**Site ID:** *Yr:* *State:* *County:* *Pedon #:*	**Soil Survey Area:**	**MLRA/LRU:**	**Transect:** *ID:* *Stop#:* *Interval:*

Landscape:	**Landform:**	**Microfeature:**	**Anthro:**	**Elevation:**	**Aspect:**	**Slope (%):**	**Slope Complexity:**	**Slope Shape:** *(Up & Dn / Across)*

Hillslope Profile Position:	**Geom. Component:**	**Microrelief:**	**Physio. Division:**	**Physio. Province:**	**Physio. Section:**	**State Physio. Area:**	**Local Physio. Area:**

Drainage:	**Flooding:** **Ponding:**	**Soil Moisture Status:**	**K_{sat}:**	**Land Cover / Use:**

Parent Material:	**Bedrock:** *Kind:* *Fract.:* *Hard.:* *Depth:*	**Lithostrat. Units:** *Group:* *Formation:* *Member:*

Erosion: *Kind:* *Degree:*	**Surface Frag %:** *GR:* *CB:* *ST:* *BD:* *CN:* *FL:* *Kind:*	**P.S. Control Section:** *Ave. Clay%:* *Ave. Rock Frag %:* *Depth Range:*

Diagnostic Horz. / Prop.: *Kind:* *Depth:*

VEGETATION:

SYMBOL	COMMON NAME	% GD COVER

MISCELLANEOUS FIELD NOTES / SKETCH:

Figure 7-1.—continued

Component Name:						Map Unit Symbol:					Date:

	Obser. Method	Horizon	Depth (in) (cm)	Bnd	Matrix Color Dry	Moist	Texture	Rock Frags Knd % Rnd Sz	Structure Grade Sz Type	Consistence Dry	Mst	Stk	Pls	Notes
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														

	Redoximorphic Features % Sz Cn Hd Sp Kd Loc Bd Col	Concentrations % Sz Cn Hd Sp Kd Loc Bd Col	Ped / V. Surface Features % Dst Cont Kd Loc Col	Roots Qty Sz Loc	Pores Qty Sz Shp	pH, method Effer (agent) Clay % Sand %	Notes
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

A standard form can serve as a checklist of characteristics that should be recorded. A checklist is especially valuable for beginning soil scientists because it reminds them to record, at minimum, data for the listed properties. Observations, however, should not stop with the listed properties. There is a strong tendency to record the information required by the form and no more. Thus, a form designed to set a minimum on the amount of information recorded also tends to set a maximum. Good soil profile descriptions typically require information beyond that needed to complete the form. Free-form notes are commonly used for this purpose.

Standard forms are useful for recording the day-to-day observations made during mapping. Many such notes are not full descriptions of pedons. These abbreviated descriptions typically can be made on a standard form more easily than they can be written in narrative form. Abbreviated notes are also useful in recording many observations during field reviews and when transecting. For these and similar purposes, the forms make note-taking easier and lessen the risk of recording an inadequate description. Complete descriptions of pedons, such as those made when soils are sampled for special studies or those of the typical pedons of soil series or map unit components, generally require a more comprehensive form or recording device so that all characteristics can be adequately described.

Standard forms, whether in hard-copy or electronic format, generally require the use of abbreviations or symbols due to limited space. These abbreviations or symbols should follow a standard format so that the recorded information can be readily and accurately interpreted by others and correctly transcribed to standard terminology. The codes in the *Field Book for Describing and Sampling Soils* are examples (Schoeneberger et al., 2012).

All soil profile descriptions, regardless of their completeness or the format in which they are recorded, should become a part of the permanent record of the soil survey area so that they are available for use by others.

Photographs

Photographs are a significant component of soil survey data collection and documentation. They can illustrate important things about an individual soil or a soil catena in soil survey reports, scientific journals, textbooks, and periodicals. They can be included in any electronic presentation of soil survey data to end users. Good photographs provide records and reference sources of basic soil information. Taking photographs needs to be planned early in the soil survey.

Photographs that include a scale are useful in estimating volume, area, or size distribution. The comparison of coarse fragments in a soil against photographs of known quantities of coarse fragments improves the reliability of estimates. Similar photographic standards can be used to estimate volume or size of nodules and concretions, mottles, roots, pores, and rock fragments. In a similar manner, photographic standards can be used in estimating area or the special arrangement of surface features and land use.

Equipment for Field Use

A good-quality camera is important in obtaining high-quality photos. Digital cameras are the general norm today. A digital camera allows the image file, along with its respective metadata, to be stored in a database file system for later use. The camera needs to provide resolution greater than 8 megapixels (at least 16 megapixels is preferred) to produce high-quality images. The ability to vary the aperture and exposure time settings is desirable. Many of the larger point-and-shoot cameras and 35-mm single-lens reflex digital cameras are adequate.

A tripod is generally necessary, especially at shutter speeds below 1/50 second. It reduces camera movement and enables the photographer to concentrate on composition and focus. A flash is needed in some poorly lighted situations or to eliminate shadows.

Certain other items are necessary for good pictures of soil profiles. A scale that indicates horizon depth or thickness is important. A scale that does not contrast greatly with the soil, such as an unvarnished and unpainted wood rule or a brown or khaki colored cloth tape that is 5 cm by 2 m works well. Large black or yellow figures at 50-cm intervals, large ticks at 10-cm intervals, and small ticks at 5-cm intervals complete the scale. A perfectly vertical scale increases the quality of the photo, in contrast to a tilted scale.

A small spatula, kitchen fork, or narrow-bladed knife is useful in dressing the soil profile. Paint brushes of various widths and a tire pump can help clean dust from peds. A sprayer can be used to moisten the profile when necessary.

Photographing Soil Profiles

Careful planning is essential for obtaining high-quality photographs of soil profiles. A representative site is selected on a vertical cut face or in an area where a pit can be dug large enough for adequate lighting of all horizons and for the camera to be 1.5 to 2.5 m from the profile. The pit or cut face should be oriented so that the maximum amount of light will strike the prepared face at the proper angle when photographed. Better images are generally obtained when the soil profile is either in full sun or full shade. Subtle differences in soil color are often more apparent on cloudy days than in full sun. Direct exposure to full sunlight often results in a washed out image.

The profile needs to be properly prepared to bring out significant contrast in structure and color between the soil horizons. Beginning at the top, fragments of the soil can be broken off with a spatula, kitchen fork, or small knife to eliminate digging marks and expose the natural soil structure. Dust and small fragments can be brushed or blown away. Moistening the whole profile or part of it with a hand sprayer helps to obtain uniform moisture content and contrast.

Every profile should be photographed three or four times with different aperture settings, angles of light, and exposure times. Notes should be made immediately after each photograph is taken to record location and date, complete description of the subject, time of day, amount and angle of light, camera setting, method of preparing the profile, and other facts that are not evident in the photograph. Besides increasing the ways the photograph can be used, good notes provide information for improving technique. If possible, a landscape photograph should accompany the soil profile photograph.

Photographing Landscapes

Landscape photographs illustrate important relationships between soils and geomorphology, vegetation, and land use and management. They should be clear and in sharp focus and have good contrast. Photographs representative of the area being mapped are the most useful.

The most important thing in landscape photography is lighting. The best pictures are made at the time of day and during the time of year when the sun lights the scene from the side. The shadows created by this lighting separate parts of the landscape and give the picture depth. If the sun is at a low angle to the horizon, shadows are generally amplified and give an image more contrast and depth. Photographs taken at midday or with direct front lighting can lack tonal gradation and, therefore, appear flat. Photographs taken on overcast days can have the same problem. A small aperture should be used to gain maximum depth of focus.

Photo composition is important. A good photograph has only one primary point of interest. Objects that clutter the photograph (e.g., utility poles, poorly maintained roads and fences, signs, and vehicles) detract from the main subject. The point of interest should not be in the center of the photograph. The "rule of thirds" for composition is useful when looking at the scene through the viewfinder. The image area can be visualized as divided into thirds both horizontally and vertically.

The center of interest should be one of the four points where these lines intersect. Sky should make up less than one-third of the image, and the camera should be kept level with the horizon. In addition, landscape photographs should be taken from a variety of angles (e.g., from a kneeling position, on a ladder, on top of a car or low building, etc.).

Close-up Photography

Many soil features, such as peds, pores, roots, rock fragments, krotovinas, redoximorphic features, concretions, and organisms, can be photographed at close range. The minimum focusing distance for most cameras used in the field allows small features to be photographed. Many cameras have a built-in macro focus feature that enables focusing within a few inches. Macro lenses are available for most 35-mm cameras. Close-up attachments for conventional lenses are also available. As with landscape photography, the lighting angle is important. Direct front lighting tends to blend texture, separation, and contrast in the photograph.

Photographing clay films and other minute soil features requires special equipment and techniques of photomicrography that are outside the range of this manual.

Metadata

For each photograph, metadata should be recorded, including the date of the photo, the geographic location, a description (caption) of what the image is intended to show, and a reference to the map unit(s) and soil components of the area.

Aggregated Data

Aggregated data capture the ranges of various physical and chemical properties of soil map units as a whole and individual soil map unit components. They include the descriptions of each soil map unit and map unit component; the detailed physical, chemical, and morphological attributes of each soil; and descriptions of the relationship of one soil map unit to another on the landscape. Aggregated soil property data generally are the data used to generate interpretive ratings for each map unit and its components.

Aggregated data are developed by summarizing the various pieces of point data that have been collected during the soil survey and referenced to a particular soil map unit or map unit component. Values for a particular soil property are commonly expressed as a range. Depending on mapping scale, map unit design, and the level of specificity of data needed for the purpose of the soil survey, the upper and lower limits and, in most cases, a representative value (RV) of the range of each soil property need to be stored in the database (e.g., clay content ranges from 18 to 27%, with an RV of 22%). The representative value is the value most likely to be found for a particular soil property and is useful in computerized interpretive models. The RV can be determined by summarizing the values recorded on the individual pieces of point data. Tacit knowledge from individual soil mappers can be used to augment recorded point data measurements.

The physical, chemical, and morphological properties of the soils included in the aggregated data generally are most or all of those that are included in the point data. They should include any properties that are used to generate interpretive ratings.

Values for many physical and chemical soil properties of a particular soil map unit or map unit component commonly vary from one topographic position to another, or from one geographic location to another, within a particular map unit or even a single delineation of a map unit. Properties can also vary from one time of the year to another, from year to year, and from one land use and/or management system to another (see chapter 9 for a discussion of dynamic soil properties). The database must have the capability to record this variability.

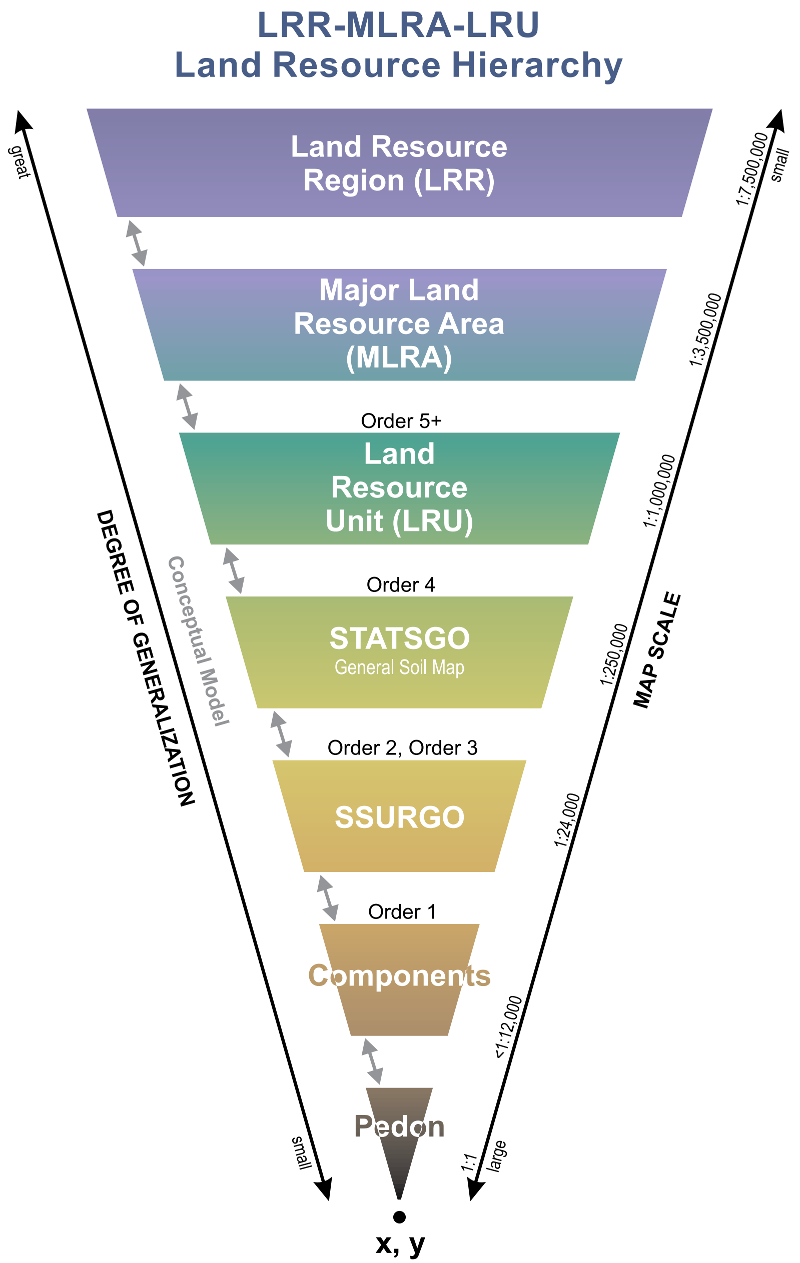
Aggregated data may represent map units that cover a particular geographic area at different map scales, for example, 1:12,000 or 1:24,000 and also 1:100,000 or 1:250,000. The differences in scale may represent a "detailed" soil map of the area and a "generalized" soil map of the same area. Map unit design and the respective map unit components will generally differ between the larger (e.g., 1:24,000) and smaller (e.g., 1:250,000) map scales. Types of soil map units and map unit design are described in more detail in chapter 4.

The U.S. National Cooperative Soil Survey and NRCS routinely produce and maintain soil data and map products at a variety of map scales. Figure 7-2 illustrates the hierarchical relationship between these aggregated data products and the original point data. The two primary soil survey products are SSURGO (Soil Survey Geographic Database) and STATSGO (U.S. General Soil Map).

Also included in the aggregated data are the various interpretive ratings for each soil map unit and each map unit component. Some ratings are applicable to the map unit as a whole (e.g., prime farmland rating), while others are applicable to the individual map unit components (e.g., limitations for building site development).

In order for soil survey data to be delivered to end users, aggregated data are commonly stored in a relational database. The database must be designed to store data for delivery and to support the various soil interpretations that are needed. Determining what will be delivered to users

Figure 7-2



Conceptual model showing the relationships and degree of generalization of data between different map scales and products. (See chapter 4 for a discussion of orders of mapping.)

at the end of the soil survey project (such as which chemical, physical, and morphological soil properties and which landscape relationships) helps in determining what data needs to be collected as point data.

Spatial Data

Spatial data is a major portion of the data collected or developed during a soil survey. It includes the geographic coordinates (e.g., latitude and longitude) that define the boundary of each map unit polygon on the soil map, whether it is in vector or raster format. It also includes the geographic coordinates for each point on the landscape where point data were collected. Boundaries of various political and physiographic areas may also be included as ancillary data layers. Other ancillary data layers, such as vegetative cover, digital elevation model (DEM) data, aerial photography, land use, and geology, are commonly used in a geographic information system (GIS) when conducting a soil survey. Derivative data layers (those developed from other data layers), such as wetness index, slope, and aspect, are also commonly used. Various soil property and interpretive maps can be developed using a GIS. A detailed discussion of digital soil mapping is provided in chapter 5. The appropriate scale and level of resolution or detail are important considerations when choosing which data layers to use.

The design of databases to house soil survey data must include a mechanism to link each individual map unit polygon on the soil map with the appropriate set of aggregated data describing the characteristics of the map unit represented by the polygon. The map unit symbol on the soil map is commonly used for this purpose.

To ensure that resulting spatial data are consistent and practicable to end users, standards for spatial data layers must be developed and/or adopted just as they are for collecting soil property data in the field. This includes the digitizing of soil maps. Establishing standards is especially important for large soil survey projects, which involve many soil survey parties. In order to get a consistent data set, the various soil survey parties must use standardized methods and techniques.

Because spatial data sets tend to be very large, adequate storage space must be considered when developing a computer system to manage soil survey data. In the U.S. soil survey database, the spatial data layer for the detailed soil maps occupies approximately one-third of the whole database. Another third is occupied by the associated aggregated soil attribute data, and another third by the included generated soil interpretation ratings. Additional storage space must be available for other data layers used in conducting the soil survey.

Soil Information Systems

As described earlier, a soil information system not only includes the actual soil survey data and information but also the various methods, computer applications, and processes used to collect, manage, store, and disseminate the data to end users. A variety of tools are available for electronically collecting soil data in the field. Data recorders can be connected to monitoring equipment to measure and record soil temperature and soil moisture at regular time intervals over an extended period of time. The data can then be imported into a permanent database.

Handheld, tablet, and laptop computers can be programmed to display a variety of field forms. Data can be manually entered into digital memory in the field and later uploaded to a central soil database. Analytical instruments in the laboratory can be connected to a computer to automate the recording of analytical test results. Global positioning systems (GPS) and digital cameras can be connected to these computers so that geographic coordinate data and photographs can be linked to other data being collected. Computers with GIS software allow the user to draw the soil map electronically in the field instead of manually on a hard copy. Capturing data electronically eliminates the need to later key the data values into the computer. This greatly increases work efficiency and eliminates a possible source of data entry error.

Techniques are being developed to allow the field soil scientist to generate a preliminary soil map using computer algorithms or programs that replicate the interaction of the five soil-forming factors, i.e., topography, climate, parent material, living organisms (especially native vegetation), and time. These algorithms use logic developed by soil scientists knowledgeable of the area being surveyed. This approach to developing the soil map, referred to as digital soil mapping, is discussed in detail in chapter 5.

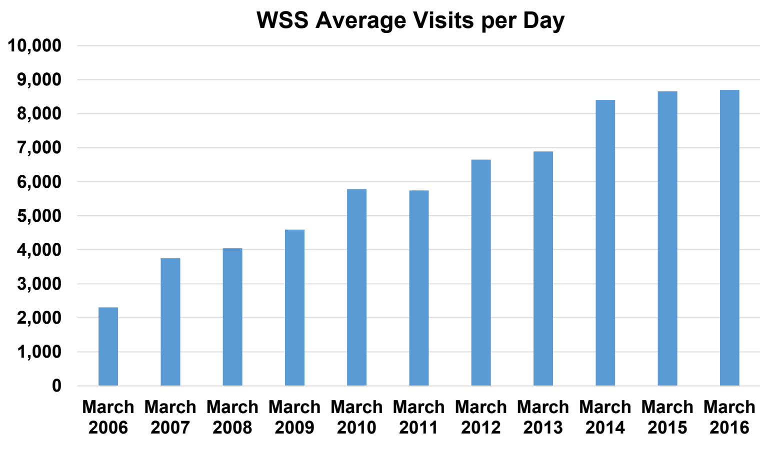
Computer applications are very useful in managing, editing, and delivering soil survey data collected in the field. They provide the capability to more readily update the soil maps and associated data and to keep the information current. Thus, they allow quicker and easier regeneration of end products and publication of the updated information.

As with any computerized system, the system itself needs to be kept up-to-date. New versions of software will need to be installed. Computer hardware eventually will need to be repaired or replaced. People will need to be trained on how to use the system. Issues and questions will occur on a day-to-day basis as problems arise with the system. They will require personnel with information technology skills as well as those with soil business skills.

Uses of Soil Survey Information

The demand and use of soil data and information is growing at a rapid pace. Figure 7-3 illustrates the increased number of users of NRCS's Web Soil Survey application. Web Soil Survey (Soil Survey Staff, 2016) was implemented in 2005 and is the agency's primary public distribution tool for official soil survey data and information. The variety of users is also expanding. Soil surveys most commonly are made for areas that have more than one kind of important land use and for users who have varied interests and needs. These needs may be few and noncomplex, as in areas of extensive land use where change is not expected, or they may be many and complex, as in areas of intensive land use where changes are expected.

Figure 7-3



An illustration of the increased number of users of NRCS's Web Soil Survey (WSS) application.

Predictions for uses of soils other than farming, grazing, wildlife habitat, and forestry have tended to concentrate on limitations of soils for the intended uses. Where investment per unit of area is high, modifying the soil to improve its suitability for the intended use may be economically feasible. Soil scientists work with engineers and others to develop ways of improving soils for specific uses. Such predictions are increasingly important in areas where the demand on soil resources is high.

The information assembled in a soil survey may be used to predict or estimate the potentials and limitations of soils for many specific uses. The information must be interpreted in forms that can be used by professional planners and others. A soil survey represents only part of the information that is used to make land management plans, but it is an important part. Chapter 8 discusses soil interpretations in detail.

The predictions of soil surveys serve as a basis for decisions about land use and management for both small tracts and for regions consisting of several million acres. They must be evaluated along with economic, social, and environmental considerations before recommendations for land use and management can be valid.

Soil surveys are used to appraise potentials and limitations of soils in local areas having a common administrative structure. Planning at this level is sometimes called *community planning*. It applies to community units (villages, towns, townships, counties, parishes, etc.) and to trade areas that include more than one local political unit.

Soil surveys also may be used to evaluate soil resources in multi-county or multi-State areas that have problems that cannot be resolved by local political units. *Regional planning* involves land use in broad perspective and appraises large areas. It is done in less detail than community planning. Soil surveys and their interpretations for regional planning are correspondingly less detailed and less specific. Soil maps and their interpretations for regional planning must provide graphic presentations of the predominant kinds of soil of corresponding large areas.

Soil surveys provide basic information about soil resources needed for planning development of new lands or conversion of land to new uses. This information is important in planning specific land uses and the practices needed to obtain desired results. For example, if recreational use is being considered, a soil survey can indicate the limitations and potential of the soil(s) in the area of interest for recreational uses, such as playgrounds, paths and trails, or off-road vehicle use. It can help a landscape architect properly design the area. A contractor can use the soil survey in planning, grading, and implementing an erosion-control program during construction. A horticulturist can use it in selecting suitable vegetation for landscaping.

Soil surveys provide a basis for decisions about the kind and intensity of land management, including those operations that must be combined for satisfactory soil performance. For example, soil survey information is useful in planning, designing, and implementing an irrigation system for a farm. Information regarding the kind of soil(s) and associated characteristics helps in determining the length of run, water application rate, soil amendment needs, leaching requirements, general drainage requirements, and field practices for maintaining optimum soil conditions for plant growth.

Soil surveys are also useful in locating possible sources of sand, gravel, or topsoil. They are an important component of technology transfer from agricultural research fields and plots to other areas with similar soils. Knowledge about the use and management of soils has been spread by applying experience from one location to other areas with the same or similar soils and related conditions.

The hazards of nutritional deficiencies for plants, and even animals, can be predicted from soil maps if the relationships of deficiencies to individual soils are established. In recent years, important relationships have been discovered between many soils and their deficiencies of copper, boron, manganese, molybdenum, iron, cobalt, chromium, selenium, and zinc. The relationships between soils and deficiencies of phosphorus, potassium, nitrogen, magnesium, and sulfur are widely known. Relationships of soils to some toxic chemical elements have also been established. However, many soils have not been characterized for these conditions (especially for trace elements) and more research is needed.

Soil surveys commonly provide essential data and information for the compilation of general soil maps. Many soil surveys are done for purposes that require relatively intense field investigation and map scales of about 1:12,000 to 1:24,000. However, a smaller scale soil map with more broadly defined units may be better for developing land use plans for large areas. General soil map scales range from about 1:100,000 to 1:1,000,000 and provide an overview of the location and extent of dominant soils in a large area. A general soil map can be made by grouping units of the large-scale soil maps and generalizing the map detail. The resulting map units may be more useful for the intended use. The amount of information that can be given about the units on a general soil map—and, therefore, the number of feasible interpretations—depends on the degree of generalization of the map units, which is determined by the map scale. Computer applications such as GIS greatly facilitate the summarization and generalization of detailed soil survey data during the development of the smaller scale soil map units.

Small-scale soil maps can provide a basis for comparison of broadly defined capabilities and limitations that relate to the soil on regional, national, and even worldwide scales. International cooperation among soil scientists has accomplished much in relating the different soil classification systems of various countries to one another using small-scale maps. This permits the findings of research on soils of one country to be extended to similar kinds of soil elsewhere. *Soil Taxonomy* (1975 and 1999) and the *Soil Survey Manual* (1951 and 1993) have guided soil scientists worldwide for many years. Many have contributed ideas and data to the soil survey system. As a result, the uses of soil survey data have been extended far beyond the boundaries of the countries where the data were originally obtained.

Dissemination of Soil Survey Information

Mechanisms are needed to deliver completed soil survey information to end users. Depending on the needs of the users, a variety of types, content, and formats of soil survey products may be needed. Each type of product may require a somewhat different mechanism for delivery.

Some users may want the raw data collected during the course of the soil survey project delivered to them in digital format. Others may want hard-copy printed soil maps along with the associated descriptive information of each soil map unit and the respective map unit components and interpretations. Some users may need access to the most up-to-date information available for the area and want to see it in an online computer application that allows them to zoom into a particular tract of land. They may not need or care about the data for the whole soil survey area. They may only be interested in soil survey data and interpretations that pertain to a particular land use. Other users may only be interested in soils data for larger areas for regional planning.

Some users prefer to have direct online access to soil data so that they can integrate this data with other data systems and applications on their local computer. Web services are tools that have been developed to accommodate such access. With these services, the user can connect to the database in a read-only mode and then query the spatial and tabular data for the geographic area of interest. These services also allow the user to have access to the most up-to-date data available without having to acquire and maintain the data on their local system. With the increased use of computers and geographic information systems and other applications, this method of disseminating soil survey data and information is becoming more widespread and popular.

Requests for soil survey data and information are commonly received while the survey is still in progress. Decisions must be made as to how to handle such requests and what data and/or information is suitable to be released at the time of the request. Any information provided should be marked as "preliminary" and "subject to change" until it has been fully reviewed and certified. Some requests may include the need for specialized interpretations of the data, and a mechanism should be available to provide those interpretations if at all possible.

Soil survey data and information, including both tabular and spatial data, can be delivered to end users in various formats. Tabular data include the map unit and map unit component descriptions; their physical, chemical, and morphological data; and interpretations of each soil for a variety of uses. Spatial data include the soil map unit boundaries and location for any point data that were collected within the survey area. Photographs are commonly included to illustrate the different soil landscapes within the survey area and to show significant features of the different soils. Narrative text is also included to convey information to the end users that may not be represented in the tabular data and to describe relationships between the different soils of the area.

Tabular data can be delivered to users as raw data in electronic database format, either online or in a standalone database file that can be loaded onto their local computers. The data can also be presented as formatted reports of various content. These reports can be delivered as electronic files for viewing or as hard-copy printouts. Tabular data can also be presented as thematic maps that incorporate the spatial data for the map unit delineations (see appendix 4 for examples). Depending on the scale of mapping and the map unit design, individual delineations may be represented on the map as polygons, lines, or points.

Thematic maps display a rating for each map unit delineation. If a particular soil map unit has multiple map unit components and the components may have different interpretive ratings for a particular interpretation, ratings need to be aggregated so that a single overall rating for the map unit can be delivered. This aggregated rating can then be assigned to the applicable delineations for that map unit. Various aggregation methods may be used, such as dominant component and dominant condition. For example, a map might show the distribution of a soil property, such as surface layer pH or surface layer clay content. The various interpretations, such as suitability or limitations of each soil map unit for septic tank absorption fields, can also be presented in formatted reports or as thematic maps.

Soil maps can be presented as digital files for use on a local computer. The digital files can be the raw data representing the soil map unit boundaries or contain formatted soil maps that can be viewed on the local computer or printed locally. The map unit boundaries can be presented in vector or raster format. In vector format, the map unit boundaries are defined by a series of x y coordinates (such as latitude and longitude) that, once plotted, replicate the shape of the original map unit boundaries drawn on the map. In raster format, the soil map is divided into a gridded format in which each grid cell is at a resolution that best represents the shape of the original soil map unit polygons. Popular resolutions include 10- and 30-meter, meaning that each grid cell represents an area 10 by 10 or 30 by 30 meters on the Earth's surface. Corners of each grid cell are defined by standard latitude and longitude or UTM coordinates. Both vector and raster formats have advantages and disadvantages. Soil maps can also be delivered as printed hard copies.

During the course of the soil survey project, special studies of selected soils within the survey area or region may be conducted. These studies may involve detailed laboratory examination of the physical, chemical, and mineralogical composition of the soils. Other studies may focus on the genesis of the soils or the geomorphology of the area. Results of such studies are used to help populate the soil database for the survey area and are commonly published in special soil investigative reports and scientific papers in technical journals. Papers discussing the studies are commonly presented at meetings of professional scientific organizations.

Whatever system is developed to collect, store, manage, and deliver soil survey data and information, the variability of formats and content of information disseminated must be considered. Demands for soil survey information are changing and are expected to continue to change at an even faster pace. The system will likely need to be changed to meet future needs and demands. The idea of "one size fits all" or "one product meets all user needs" is no longer appropriate. Any system that is developed to deliver soil survey information must have built-in flexibility so that it can be updated and modified to meet the ever changing needs of users. However, it is important to remember that the more flexibility one builds into the delivery system the more maintenance and upkeep cost will be required in the years to come.

History of Soil Data Management in the U.S.

The development and evolution of a national system to collect, store, manage, and disseminate soil survey data and information for the U.S. National Cooperative Soil Survey (NCSS) began in the late 1960s and early 1970s and included several iterations. As with other information technology, the pace of development and functional capacity has steadily accelerated since the mid-1990s.

The First Generation

The USDA Soil Conservation Service (SCS), renamed the Natural Resources Conservation Service (NRCS) in 1994, first established a national soil database in the early 1970s through a cooperative agreement with the Statistical Laboratory at Iowa State University (ISU) (Fortner and Price, 2012). ISU was chosen because of its long history of cooperative work with the SCS, dating back to the 1940s. Programming work for a soil database began in 1972 with automation of the soil interpretations record (SIR), or SOI-5 form, which was used primarily as an input form to generate tables on engineering uses of soils for published soil survey reports. The SOI-5 form was first developed in the late 1960s. At least one SIR was developed for each soil series recognized in the soil survey of the United States. Some soil series had more than on SIR, depending on how many phases of the series were recognized and mapped.

Computer programs were developed to store, check, and print the data. The soil interpretation record for the Cecil soil series (NC0018) was the first one stored on the ISU mainframe in 1973. In 1974, the generation of manuscript tables of soil properties for inclusion in soil survey reports was introduced. Initially, all data processing was done at ISU and a printed copy of the tables was sent through the mail. The SOI-5 forms, along with the SOI-6 forms, which were used to enter specific map unit information for the soil surveys, were mailed from SCS offices to ISU for processing. Printed copies of revised records and generated tables were mailed back to the SCS office requesting the tables. This automated table generation system replaced the very tedious, time-consuming manual process of creating tables for the published reports.

With the availability of this useful product came a much greater interest in storing data in the computer system. In 1977, the system gained the capability to automatically generate soil interpretations for 26 selected (mostly engineering) uses from the soil data stored in the database using programmed criteria. These interpretive ratings were stored in the database and printed on the hard-copy SOI-5 forms. After 1977, other enhancements were developed, including the addition of the Official Soil Series Description (OSD) and Soil Series Classification (SC) databases.

Computerization in SCS offices for processing soil survey data began in 1977 with Linolex word-processing equipment in SCS National Technical Center offices. This equipment was used to prepare manuscript tables received on magnetic tape from ISU for final publication. Remote access to ISU from SCS, in both State and regional offices, began in the early 1980s with Harris Remote Job Entry equipment. Communication was through 4800-baud dial-up communication ports. It was a time of significant change as batch software had to be redesigned for remote usage and data entry. Processing and printing of manuscripts shifted from ISU to SCS offices.

The SIR database remained operational until 1996, when it was retired after the release of the new National Soil Information

System (NASIS) software and database. About 35,000 SIRs were developed during the 24 years that the SIR database was active.

The Second Generation

Work on the second generation of the national soil database began in 1978, when SCS developed a computer program to rate soils for prime farmland and other important farmland classes and create maps for the Colorado Important Farmlands project. This project required the rating of about 4,500 soil map units in Colorado. It used national criteria for prime farmland and State criteria for farmland of State importance and unique farmland. The most difficult problem was making ratings consistent across soil survey areas. The program evaluated 10 soil characteristics and was fairly accurate in its ratings. However, a large database was required to make the ratings and the effort required to develop the database made the project unfeasible. The need for a large database, which would also be readily accessible and easy to manipulate, resulted in the development of concepts for the second generation of soil information management.

These concepts were first documented in 1980 in the first technical report for the Colorado Soil Resource Information System (SRIS). SRIS demonstrated the feasibility of integrating several natural resource databases into a common, easy-to-use data environment. SRIS included: (1) a soil map unit component database, (2) a soil interpretation database, (3) a pedon characterization database, (4) a climatology database, (5) a plant database, (6) a soil management component, and (7) a schema for the data and description of the system. SRIS was the first effort to manage soil data using a new technology called database management systems (DBMS). The new information system allowed questions relating to more than one natural resource to be answered. It facilitated easy access to soil information and allowed the data to be managed independently of the application software that accessed it, while the SIR database required a computer program to be written for each unique request. In 1982, the SRIS soil database was implemented in Colorado.

As an outgrowth of the SRIS effort, SCS established the software development staff at Fort Collins, Colorado, in 1985. The mission of this staff was to develop computer software to assist the SCS field offices. In 1987, this effort resulted in the deployment of the Computer Assisted Management and Planning System (CAMPS) field office software and the State Soil Survey Database (SSSD). SSSD, which was a UNIX-based application and used Prelude RDBMS software, was the culmination of the SRIS effort and was populated using map unit specific information and querying the SIR database. The resulting soil survey data collectively were called the Map Unit Interpretation Record (MUIR) database.

With the release of SSSD in 1987, SCS State offices were equipped with UNIX computers. The SSSD software allowed the State offices to manage their portion of the soil survey databases, which were downloaded from Iowa State University via telecommunications. The primary function of the first release of SSSD was to review the included soil data, make necessary edits, and provide a download of the MUIR database to CAMPS. The first release of SSSD provided the ability to develop reports through standard database queries and manage nontechnical soil descriptions. With this software release also came the recognition that a soil scientist position (soil dataset manager) was needed at each SCS State office to manage the soil information system.

Using SSSD, the SCS State offices could edit the soil map unit property and interpretation (MUIR) data at ISU and thus more accurately represent local conditions. The offices returned a copy of the edited data to ISU. This editing capability provided for a national collection of MUIR data in 1993. SSSD releases in 1988 through 1993 added additional capabilities. In 1988, the Pedon Description Program, version 1.0, and the Official Soil Series management and soil reports modules were released.

In 1989, the interface between the Soil Survey Geographic Database (SSURGO) and the Geographic Resource Analysis Support System (GRASS) was released. In 1989, a UNIX mail system called SoilNet and an automated version of the SOILS-6 form, which was used to record map unit data and facilitate the downloading and managing of MUIR data from ISU, were released. In 1991, the Soil Survey Schedule module was released. This module provided management, scheduling, and record-keeping software for SCS State and national offices to use in soil survey efforts. In 1993, the Hydric Soils, Range Site, and MUIR incremental update modules were released.

Although table generation remained its primary purpose, the MUIR database was soon used for more than developing soil interpretation tables for reports. SCS began to use the database to answer questions on a wide range of soil-related issues across the United States, for example, the extent of salt-affected soils, soil loss tolerance and erosion potential for determination of highly erodible land, and identification of hydric soils (wetlands). The uses of the soil database continued to expand and change until it became apparent in 1988 that SSSD and MUIR could not meet the changing needs. New information systems technology was available that could advance the use of soil survey information.

The SIR and MUIR soil database system was remarkable in that it was able to evolve in many ways over time but still kept its basic system design for about 25 years, until it was retired in 1996. At that time, the MUIR database contained data from about 2,900 soil survey areas and included approximately 250,000 soil map units. Implementation of the replacement system, the National Soil Information System (NASIS), began in 1994. Before the SSSD system was retired, the soil information in the MUIR database was converted to the new NASIS database.

The Third Generation

Development of NASIS began with the analysis and documentation of the business of soil survey from beginning to end. Teams from various levels in the U.S. National Cooperative Soil Survey (NCSS) were established to complete the requirements analysis. Using structured systems analysis, these teams documented requirements, which were passed on to contract software programmers. This analysis documented the important shift of the NCSS from producing static, printed soil survey reports to providing a dynamic database of soil information that could meet a wide range of needs and the ever growing demand for soil survey data and information.

A field data collection system was needed to ensure the integrity and completeness of the data, including geographic coordinates. The system was designed to provide users accurate and complete soil survey information based on what was observed during the soil survey process. Implicit in this idea was the ability to describe accurately the variability of soils and their properties as they occur on the landscape. This new system had to provide for a continuous update of the database as new information was gathered, so that one version of these data would be available to users at the field, State, and national levels.

NASIS had to provide a means for a variety of scientists to develop interpretation criteria and generate soil interpretations based on local, State, or national requirements. For example, at the local level there might be a need for an interpretation of soil suitability for animal waste disposal and at the national level there may be a need for a soil productivity index. To ensure consistency, these interpretations must be applied to only one nationally consistent version of the data. The system had to provide for effective and efficient data delivery, including easy access by both internal and external (non-NCSS) users. This information needed to be delivered with a common data structure, data dictionary definitions, and appropriate metadata so that users could understand the information and apply it appropriately.

NASIS System Objectives

Many weeks of analysis (discussion) and numerous follow-up meetings identified the following specific system objectives (Soil Survey Staff, 1991):

- The placement of automated tools in the hands of field office staff
- One-time data entry, so that data could be retrieved by multiple software modules in various computer programs
- A simple means of entering data in the same format as that used during data collection
- Validations to ensure proper entry of data and algorithms to provide default values
- Automated procedures for correlation and quality assurance
- Flexibility of the system to adapt to changes in procedure and standards and to new data needs and policies
- Capability to aggregate large-scale digital soil maps to smaller scales based on user-defined criteria
- Data manipulation and retrieval options for all databases and software modules that include modeling capability
- The ability to use single property values or representative values, in addition to ranges, in models
- Capability to indicate confidence limits and the reliability of map unit data
- Continuous update of national, State, and field office soil survey databases
- Access to State and national databases to enter or edit data managed at appropriate office level
- Permanent storage of all soil survey documentation
- Capability to transfer data files between various kinds of equipment
- Two-way linkages to other natural resource databases
- Software modules that are interactive, menu driven, and user friendly
- Training on how to use the new system

NASIS Software Development and Implementation

As with the SSSD software, the initial releases of the NASIS software were in successive yearly versions. New or updated functions and capabilities were added with each release.

- Version 1.0, released in 1994, was implemented in each SCS State office. Each State held and managed the data for their respective soil survey areas. NASIS 1.0 was developed in the C+ programming language using the X Window system, a UNIX-based graphics window system. Similar to the Microsoft Windows application that comes on many personal computers, the X Window system is a graphical user interface (GUI). INFORMIX was selected as the NASIS database management software (DBMS) largely because of its security features. This proprietary design enabled the construction of a system that prevents most accidental or intentional corruption of data. NASIS allows different data records in the database to be owned by different individual users or groups of users, so that only qualified scientists can edit or create data. The owner of an object has the authority to change data as needed. Individual or group ownership can be established as needed.

  Version 1.0 provided validation and conversion of MUIR data to the NASIS database structure; a security system and controls; an operational data dictionary; editors for areas, legends, and data map units; and online help. Individual NASIS users accessed the system using a Web-browser-based interface that connected to their respective State database for data input and editing.
- Version 2.0, released in 1995, provided Cut, Copy, and Paste functions for data objects, a query editor and manager, global assign functions, report generation, and an enhanced online help system.
- Version 3.0, released in 1996, provided calculation and validation routines for data and the ability to create criteria for interpretations and generate interpretations. This was a major step that allowed for the creation of specialized interpretive criteria and the evaluation of each map unit component against those criteria.
- Version 3.1, released in 1997, provided for the replacement of the national MUIR data with NASIS data and consolidated NASIS databases from individual State offices to the original 17 MLRA soil survey regional offices. It provided downloads to the NRCS field office computing system (FOCS) and downloads of SSURGO-format datasets. Releases of versions 1.0 through 3.1 primarily addressed the development and management of map unit data.

- Version 4.0, released in 1998, provided data tables for storing site and pedon description data and incorporated capabilities for input of and access to pedon descriptions and soil site information. It also replicated storage of national map unit data via the Internet at ISU and data sharing via the Internet.
- Version 5.0, released in 2001, further consolidated the NASIS database to a central server environment at the NRCS Information Technology Center in Fort Collins, Colorado. Data storage at ISU was discontinued.
- Version 5.2, released in 2003, included the capability to export datasets to the Soil Data Warehouse for each soil survey area.
- Also in 2003, Version 2.0 of the Soil Survey Geographic (SSURGO) data model was adopted and implemented for the distribution of official soil survey tabular attribute data. Concurrently with this release, the Soil Data Warehouse and Soil Data Mart were implemented (see below).
- Beginning in 2004, development of a new generation of NASIS began. As a result, NASIS 6.0 was released in 2010. This version introduced a client-server-based environment where the user interacted with the national soil database on the central server using a version of the NASIS application on their local personal computer. It is a Microsoft Windows-based system using a .NET operating system and SQL Server DBMS.

  NASIS 6.0 introduced the concept of managing soil survey data by projects rather than the traditional soil survey areas (typically county-based legends). This concept promoted designing map units on the basis of their natural geographic occurrence rather than limiting their spatial extent to geopolitical boundaries. A process of data updating and recorrelation was begun to ensure a seamless join of spatial and attribute data between soil survey areas. As a result, soil properties, qualities, and interpretations of map units and their components extend across geopolitical boundaries to their full natural extent.
- Periodic minor releases of NASIS continued to add new functionalities to the system and refine the data model as needs changed.
- In 2014, Version 7.0 of the NASIS database was released. It included the addition of data tables to house vegetation-related point data collected as part of the Ecological Site Inventory. These data will be used to develop Ecological Site Descriptions of the

U.S. The data model allows pedon descriptions and laboratory analysis data from a given location to be related to vegetation data from the same location. Existing vegetation inventory data from other existing databases will be converted and imported into the new NASIS tables.

- In 2016, Version 7.0 of the NASIS application was released. It gave NASIS users the ability to create user-specific forms, which they could use (instead of the traditional NASIS edit screens) to create, view, and edit data.

Digitization of Soil Survey Maps

Interest in digitizing NCSS soil maps began with the introduction of the Map Information Assembly and Display System (MIADS) to SCS in 1971. MIADS was a cell-based method of digitizing and was primarily used for creating interpretive data. Oklahoma was one of the States that digitized most or all of their soil surveys using this system. Efforts to find an efficient, feasible, and consistent method to digitize soil maps using the line-segment method continued. Various methods were tested. In 1990, standard policies and procedures for digitizing new and updated soil surveys, issued as "National Instruction No. 170-303 CGI—Technical Specifications for Digitizing Detailed Soil Maps," were adopted by the SCS Soil Survey Division. The intent of these standards was to establish a set of policies and procedures for everyone to use and so ensure products have consistent quality. Getting soil maps digitized was a slow progress and involved a variety of in-house personnel as well as contractors.

NRCS started the SSURGO Soil Survey Digitizing Initiative in 1995 with a special appropriation of funds. Although some soil surveys had been digitized as early as 1975, the SSURGO initiative was the first concerted effort to digitize all of the soil surveys in the U.S. It began a massive 12-year project to convert hard-copy soil maps to SSURGO and lasted through 2007. During this period, many soil surveys were updated as they were digitized. Digitizing centers were established to do the actual digitizing work or to conduct quality reviews of work done by others.

Beginning in the mid- to late-1990s, digitizing soil maps became part of the actual soil survey project work. Digital maps are one of the initial products of new or updated soil surveys. A soil survey project is not considered complete until the digital maps are available and meet established standards.

Soil Data Warehouse and Soil Data Mart

Early business analysis for a national soil information system identified the need for a single point of delivery of official soil survey data and information and the ability to archive versions of official data. (The NASIS database and application are intended primarily for internal use in developing and managing soil survey data and not for public access or delivery of data.) To meet this need, the Soil Data Warehouse (SDW) and Soil Data Mart (SDM) were deployed in 2003. By that time, significant progress was being made in digitizing soil survey maps.

The SDW is designed to hold all versions of official soil survey data (both SSURGO2 and STATSGO) produced since 2003, including not only tabular attribute data and digital spatial data but also metadata files that comply with the standards of the Federal Geographic Data Committee (FGDC). The SDM database contains only the most current version of official data and initially served as the data-distribution site. It provided a public access point for the data and allowed the user either to download digital SSURGO datasets in a standard format for use in a local geographic information system (GIS) or to run standard soil survey reports on selected datasets. In 2013, the data distribution function of the SDM was migrated to the Web Soil Survey (see below).

SSURGO Access Database Template

When data were downloaded from the Soil Data Mart, the attribute data tables were in a series of unrelated text files. For the data to be used, they first had to be loaded into a relational database format of the user's choosing. A database template in Microsoft Access format was developed for this purpose. The template includes macros for loading the data as well as standard queries and reports for viewing the data. It was included with each data download.

Soil Data Viewer

Soil Data Viewer (SDV) is an application developed as a plug-in extension of ESRI ArcMap for viewing digital soil maps downloaded from the Soil Data Mart and later from Web Soil Survey. It requires the SSURGO Access Database Template (described above) for accessing the attribute data. It was developed to help shield the user from some of the complexity of the attribute data structure. SDV includes a series of rules for aggregating soil properties and interpretations of individual map unit components to a single value for the respective map units for display in the GIS-generated thematic maps. This tool is available to the public.

Web Soil Survey

As the digitizing of soil survey maps progressed and the Soil Data Mart became more fully populated with data, users began to ask questions (e.g., Why could they not view the soil maps from the SDM online? Why did they need to download the data?). Many users did not have the equipment or expertise to work with the data themselves. To address this issue, the Web Soil Survey (WSS) was developed and first deployed in August 2005. It provides a publicly accessible online interface to the national collection of SSURGO datasets in the SDM database. In WSS, the user must first delineate the area of interest (AOI) for which they want to obtain soil survey data and information. The AOI may be an individual farm or ranch, an individual farm field, a watershed drainage area, or a whole soil survey area. It is also not limited to part of a single soil survey area but can span multiple survey areas. Users can define their AOI by using graphical tools that are part of the WSS interface, or they can upload a boundary developed in their local GIS.

After delineating the AOI, the WSS user can display the soil map for the selected area, generate interpretive or thematic maps for a wide variety of uses or selected soil properties, print individual maps or accumulate them into a composite report, or download the SSURGO data for the selected area. Data related to thematic maps are also included with SSURGO data downloads so that the user can generate similar maps using their local GIS software.

WSS merges the datasets and displays data and maps in a single layer. It uses the same rule set that Soil Data Viewer uses for aggregating data for display at the map unit level. It also provides the capability to download the underlying SSURGO dataset clipped to the AOI boundary for use in a local GIS.

In 2013, Version 3.0 of WSS was released. With this release the process of downloading official soil survey data, both SSURGO2 and STATSGO, was transferred from the Soil Data Mart to Web Soil Survey. SSURGO2 datasets are available for whole soil survey areas for the United States. STATSGO data are available as individual State datasets or for the whole U.S. As was the case with SDM, each data download includes a copy of the SSURGO Access Database Template.

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CHAPTER 8

Interpretations: The Impact of Soil Properties on Land Use

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Introduction

This chapter explains the concepts and principles used in the interpretation of soil property data to evaluate or predict suitabilities, limitations, or potentials of soils for a variety of uses. Soil survey information answers a wide range of soil-related questions, such as which crops will grow where and what are the best locations for infrastructure. Soil information can be used alone or as one layer of information in integrated systems that also consider other natural resources, demographics, climate, and ecological and environmental factors in decision making.

In the United States, soil survey data and soil interpretive information from the official Soil Survey Geographic Database (SSURGO) are a major part of a growing number of geographic information systems (GIS) and models. These systems and models are used in regional planning, erosion prediction, estimating crop yields, timber and energy management, urban planning, public health considerations, and determining a soil's ability to perform certain ecosystem services (such as carbon storage) that can affect global climates. Historically, soil survey interpretations primarily have been used to provide the public with soil interpretive predictions specific to a land use. Soil interpretation in the U.S. aims to quantify the soil function parameters expounded by the Food and Agriculture Organization of the United Nations. Ecosystem services performed by soil include provision of construction materials, filtering of water, providing habitat for organisms, sequestering carbon, flood mitigation, anchoring human infrastructure, supporting the growth of crops, and being a reservoir of genetic resources.

For the National Cooperative Soil Survey (NCSS) program, interpretive information is available in a public database and displayed in Web Soil Survey (WSS) (Soil Survey Staff, 2016). The baseline data and criteria are revised and refined continuously. The interpretive information is kept up to date by yearly refreshes. (The appendices provide examples of soil interpretations available through WSS, including thematic maps of soil properties and suitability ratings as well as tabular reports.) Soil interpretation reflects the capacity of the soil to support various uses and management practices. The level of data collection needed to execute the current interpretations program of the NCSS is outlined in relevant parts of the *National Soil Survey Handbook* (USDA-NRCS, 2016).

Generally, preparation of interpretations involves the following steps: (1) assembling information about soils and their landscapes, (2) deriving inferences, rules, and models for predicting the impact of soil properties on soil behavior under specific land uses, and (3) integrating these predictions into generalizations for each map unit component.

Soil interpretations provide numerical and descriptive information pertaining to a wide range of soil interpretive predictions. This information can be expressed as classes, indexes, or values with different units of measure. For example, particle-size data can be inferred from soil separates of sand, silt, and clay; USDA texture classes; or Unified soil classes. Generally, soil interpretations are made for specified uses and are reported in the form of limitations, suitabilities, or potentials. For limitations, soil properties that limit land use or establish the severity of limitation are typically indicated. For suitabilities, soil properties that determine a soil's suitable characteristics may be given. In addition, soil interpretations, either as limitations or suitabilities, may be incorporated into potential ratings along with other resource data and interpretive information. The interpretive results can be presented in tables or in maps that depict the spatial extent at scales appropriate for a specific application.

The predicted practicality of alternative management options can be derived from soil interpretations. For any particular land use, soil responses to management alternatives can be predicted, the kinds of management needed can be identified, and the benefit-to-cost relationship for the management selected can be evaluated.

Considerations for Developing Soil Interpretations

An interpretation, such as limitations for septic tank absorption fields, provides information for a specific purpose and rarely is adaptable without modification to other purposes. Application of interpretations for a specific land area has an inherent constraint related to the scale of mapping and the composition variability within a map unit. This constraint is related to how soil surveys are made and the spatial relationship of the area of interest to the map unit delineations. These concerns are particularly significant for land areas for which large capital expenditures are contemplated (e.g., homesites). These areas are typically small relative to the size of map unit delineations and may occur on a dissimilar minor component that has interpretations that differ from those of the major components of the unit. These concerns are even greater for multi-taxa units. See chapter 4 for a complete discussion of map units, map unit components, and mapping scale.

Inherent soil property spatial variability defines the resolution of soil interpretations and the precision of soil behavior predictions for specific areas. Soil survey interpretations are rarely suitable for such onsite evaluations as homesites without further evaluations at the specific site. Soil interpretations do provide information on the likelihood that an area is suitable for a particular land use and so are valuable for screening areas for a planned use. This likelihood may be expressed as a suitability or a limitation.

Specific soil behavior predictions are commonly presented as the degree of limitation imposed by one or more soil properties. Limitations posed by a particular soil property must be considered along with those of other soil properties to determine which property poses the most serious limitation. A high shrink-swell potential, for example, may be the only limiting soil property for building houses with basements for some soils. However, other soils that have a high shrink-swell potential may also have bedrock at shallow depths, and shallow depth to bedrock may represent a greater limitation than shrink-swell. Relatedly, some soils that have a low shrink-swell potential, which is favorable for homesites, may have limitations because of wetness, flooding, slope, etc. The degree of limitation imposed by a soil property on a land use may be thought of in terms of the added cost to perform the land use relative to a less limiting soil. If necessary, any limitation may be overcome, but the additional expense of installation, maintenance, and decreased performance may be prohibitive.

Other soil behavior predictions are presented in terms of how suitable a soil is for a particular land use. Historically, soils have been rated for their suitability as a material, such as topsoil or a source of sand. Soil productivity indices for crops and plants are also typically reported in terms of suitability. The underlying principle is that the soil will be used as it exists with no measures to overcome whatever makes the soil less suitable for a function. The major disadvantage of a suitability interpretation is that all of the soil and site properties that might impact the land use must be identified and evaluated. If a property that does not exist in the database is identified as being important, it must be derived or included in some manner in the rating process. Omission of a soil property that is not suitable will cause invalid positive ratings.

Certain considerations that determine economic value of land are not part of soil interpretations but are an integral part of determining soil potentials for a given land use. For example, local groups consider the location of a land area in relation to roads, markets, and other services when developing soil potential ratings based on costs to maintain the soil resource versus benefits derived.

Interpretations are sensitive to changes in technology and land uses. Crop yields generally have increased over time, and new practices may reduce limitations for nonagricultural uses. For example, the introduction of reinforced concrete slab-on-ground house construction has markedly reduced the limitation of shrink-swell for small building construction. Additionally, new uses of land or changes in technology will require new prediction models for soil interpretations.

Soil properties can also be interpreted in terms of the favorability of a soil for the growth of certain fungi, bacteria, and other organisms that are either unwanted (such as a disease-causing organism) or economically desirable. While the land is not necessarily managed for a particular organism, prediction of the presence or absence of the organism can be useful. Also, soil properties can be used to assess the propensity of a soil to retain or transmit certain chemicals or energy (heat and cold). This propensity is not a limitation or a suitability, because it does not indicate a hazard or desirability, but rather a tendency.

Finally, interpretations based on properties of the soil in place are only applicable if characteristics of the land area are similar to what they were when soil mapping was done. New interpretations may be required if the soil and site properties have been affected by physical movement, compaction, or bulking of soil material or changes in patterns of water states by irrigation, drainage, or alteration of runoff by construction.

Interpretive Models

Interpretations are models that predict soil behavior based on soil physical and chemical attributes. The spectra of soil, site, and climatic properties that are available are addressed later in the chapter. The generalizations of soil behavior are based largely on a known or obtainable set of soil and site properties that are maintained in a database or predicted for each soil component. These soil properties or characteristics can be used to predict other attributes of soil, such as potential for frost heave or concrete corrosion. In addition, documented experiences with soils having certain sets of properties are used to generalize or predict soil behavior for many land uses. These generalizations are commonly formalized in interpretive models for computer-generated ratings.

Interpretive models may be based on knowledge of how soils perform under different uses or based on research data and/or inferences. These models may contain a narrow set of inferences for specific uses or applications (e.g., limitation of the soil for trench-type sanitary landfill), or they may have a highly integrated set of inferences about complex practices that are based on a large number of considerations, only some of which are interpretive soil properties (such as the land capability classification system; Klingebiel and Montgomery, 1961). Like other processes in a soil survey, the process of developing interpretations for a specific land use follows a scientific method. The soil scientist or group preparing the criteria reviews the literature, interviews experts, makes observations of soil performance under the specific use, develops a set of criteria using basic soil properties, tests the criteria, and finally adopts the system. The process rarely becomes static; as new technologies become available, the criteria must be reevaluated.

Developing a Soil Interpretation

One of the first tasks in developing an interpretation is to create a criteria table of the soil, site, and climatic attributes that are thought to impact the land use. Table 8-1 provides an example. It contains a comprehensive set of criteria for interpreting soils for septic tank absorption fields. Some of the included criteria may not be applicable in some places (e.g., areas of permafrost). Using this example, the soil scientist or group developing an interpretation first determines a list of soil properties that are known, or thought to be, important for septic tank absorption fields. Depth to water table, saturated hydraulic conductivity, depth to bedrock, depth to cemented pan, depth to permafrost, slope, flooding, ponding, fragments > 75 mm, and susceptibility to downslope movement or subsidence are considered important properties. After determining the list of soil properties, the soil scientist or group develops limits for each property and each class. This iterative phase is commonly the most difficult. The initial set of criteria is tested in different areas of the country under a wide variety of soil conditions. Results of the tests may require adjustments to the criteria and retesting. Once the limits are set, they may be arrayed in the table according to degree of severity or importance. Soil interpretations are models for predicting

Table 8-1

Interpretive Soil Properties and Limitation Classes for Septic Tank Absorption Fields

Interpretive soil property	Limitation class: Not limited	Limitation class: Somewhat limited	Limitation class: Very limited	Limiting feature
Total subsidence (cm)	---	---	> 60	Subsidence
Flooding	None	Rare	Very frequent, frequent, occasional	Flooding
Bedrock depth (m)	> 1.8	1–1.8	< 1	Too shallow
Cemented pan depth (m)	> 1.8	1–1.8	< 1	Too shallow
Free water occurrence (m)	> 1.8	1–1.8	< 1	Depth to saturation
Saturated hydraulic conductivity (µm/s)—				
Minimum 0.6 to 1.5 m [a/]	10–40	4–10	< 4	Slow water movement
Maximum 0.6 to 1 m [a/]			> 40	Poor filter
Slope (pct)	< 8	8–15	> 15	Too steep
Fragments > 75 mm [b/]	< 25	25–50	> 50	Large stones
Downslope movement			[c/]	Landslides
Permafrost			[d/]	Permafrost

[a/] 0.6 to 1.5 m pertains to the water transmission rate; 0.6 to 1 m pertains to filtration capacity.
[b/] Weighted average to 1 m.
[c/] Rate "severe" if occurs.
[d/] Rate "severe" if occurs above a variable critical depth (see discussion of the interpretive soil property).

how soils respond under a specific use. They use a set of rules or criteria that are based on the basic soil properties, modeled properties, or classes of properties. In some cases, it may be necessary to model a subset or intermediate interpretation to evaluate such properties as potential frost action, corrosivity, or potential for mass movement.

Interpretations are mostly developed in response to user needs; thus, the development process must include input from users and professionals in other disciplines. User feedback is crucial in the iterative process of refining a specific interpretation.

The "interpretive soil property" is the attribute to be provided to the model, generally by extraction from the database. However, the criteria in the table can be applied to individual soils without the use of a computer, depending on the circumstances. The "limitation classes" are determined by the team of experts in collaboration with the projected users of the interpretation. The magnitudes of the soil attributes at the critical thresholds of impact and the presence or absence of some condition are also established by the team of experts. The "limiting feature" is the reason that particular soil attribute limits the land use.

Table 8-2 illustrates how criteria are applied locally to a component of Aksarben soils. Tables 8-1 and 8-2 illustrate the process of developing an interpretation. Note that in table 8-2, only those soil properties that are applicable to the local area are required, so the number of properties evaluated is less than the number included in table 8-1.

Table 8-2

Values of Applicable Interpretive Properties for Septic Systems for an Aksarben Component

Property	Limitation Class			Values
	Not limited	Somewhat limited	Very limited	
Flooding	X			None
Bedrock depth	X			> 1.8 m
Free water occurrence	X			> 1.8 m
Saturated hydraulic conductivity—				
Min. 0.6 to 1.5 m			X	2 µm/s
Max. 0.6 to 1 m	X			6 µm/s
Slope		X		8 percent
Fragments > 75 mm	X			0 percent

In the example above, flooding, soil depth, depth to free water, and rock fragment content are not limiting. The slope, at 8 percent, presents some limitation. The maximum saturated hydraulic conductivity in the depth range of 0.6 to 1.0 m (i.e., 6 micrometers per second) is not limiting. However, the minimum saturated hydraulic conductivity in the depth range of 0.6 to 1.5 m (i.e., 2 micrometers per second) is a severe limitation as it causes slow water movement.

Testing and Reevaluation

The interpretive model is under continuous scrutiny through user feedback, ranging from local homeowners' associations and units of government to national environmental agencies and organizations. Soil scientists continue testing of interpretations through observations and discussions with local user groups during the soil survey process.

Current U.S. Interpretive System

This section describes how soil interpretations are developed and managed in the National Cooperative Soil Survey (NCSS). The commonly used system of placing the soil into an interpretive limitation or suitability class is discussed briefly, then a newer and more sophisticated system is explained. The newer system uses fuzzy system concepts to more fully express the degree of membership of a soil in a particular interpretive class.

Overview of the Interpretations System

Historically, soil interpretation results were expressed as limitation or suitability classes. *Limitation style* interpretations typically placed soils into three interpretive classes, such as "slight," "moderate," or "severe," and reported which soil properties or features were restrictive to the land use. An example would be a "severe" rating for dwellings with basements for soils with a high shrink-swell potential. *Suitability style* interpretations placed soils into "good," "fair," or "poor" interpretive classes and reported the soil properties or features that make the soil least suitable for the use or management practice. An example would be a "good" rating for potential sand source. Actually, the class names for interpretive results may take any form that suits the needs of the user. Some users prefer a positive statement with a listing of limiting properties. Many U.S. soil surveys were made with interpretations expressed this way.

Fuzzy System Concepts

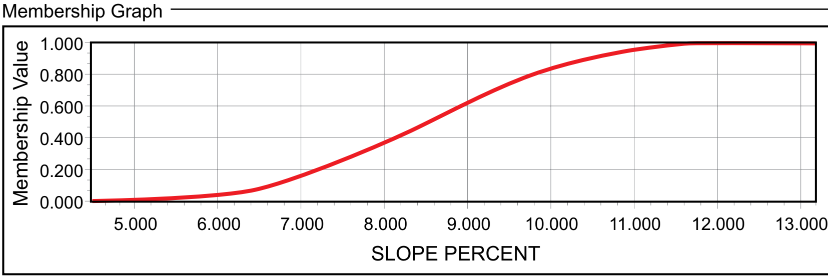
The current methodology for developing and processing interpretive information allows not only class names to be reported but also numeric ratings that indicate the degree of limitation or suitability of a soil for a land use or management practice. These index numbers are based on fuzzy system concepts (Cox and O'Hagan, 1998) that describe a soil's membership in the set of soils that are either limiting or suitable for the specified use. Using this technology, soil map units and map unit components can be described as full members, partial members, or non-members of a defined interpretive group. This membership is presented as a numeric index ranging from 0 to 1, where the higher the index number the more fully a soil is a member of the set and thus the greater the degree of limitation or suitability for a specific use.

A team of subject matter experts evaluates the impact of each soil property on the specific land use and sets the interpretive thresholds. For a limitation style interpretation, an attribute such as slope gradient may have a level that is not limiting and the associated index is 0, meaning it is absolutely false that this soil is a member of the set of soils limited by slope gradient. As slope increases, a level is reached where the soil cannot be successfully used for a particular land use and the associated index is 1, meaning it is absolutely true that this soil is in the set of soils limited by slope gradient. This relationship is depicted by a curve called an evaluation or a membership function (see figure 8-1).

Figure 8-1

	Low Value	High Value
Data	5	12

Membership Graph



Membership function for slope percent for a limitation style interpretation where a membership value of 1 denotes limiting and lower values denote less limiting (i.e., more gentle slopes).

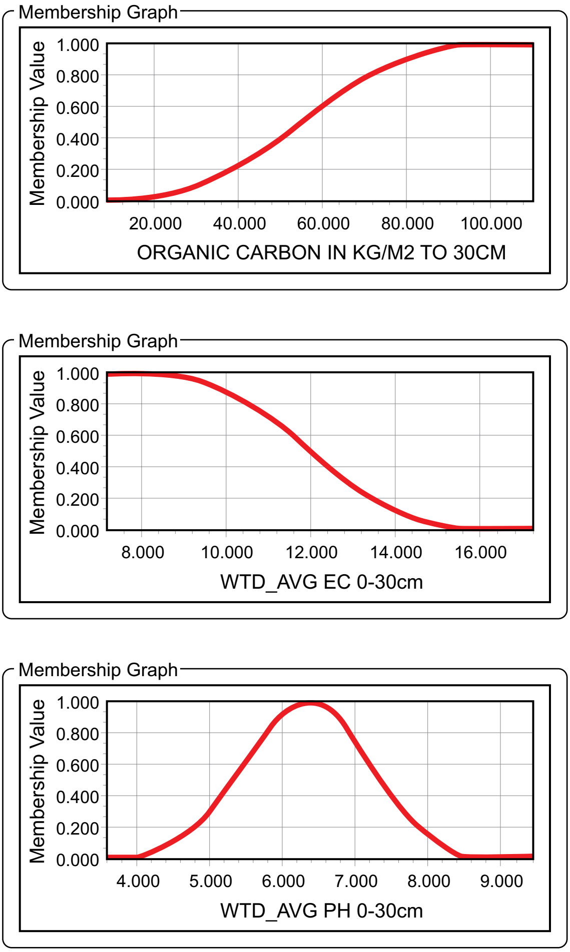
In the example given in figure 8-1, when a soil has a slope of 12 percent or greater, it is absolutely true that this soil is limited for the land use. When the slope is 5 percent or less, it is absolutely false that this soil is limited. Slopes between 5 and 12 are given numerical ratings that indicate the degree of partial membership in the set of soils that are limited due to slope. The character of the curve is also determined by the team of experts.

The overall automated system has three parts: (1) an attribute that is extracted from the database, (2) an evaluation of the membership value of the attribute, and (3) a reason or descriptive term assigned to the membership value (referred to as a "rule"). A set of these is associated with each soil, site, or climatic attribute. A particular depth range can be specified for horizon data, and items such as seasonal wetness, flooding, and ponding can be parsed by month. If needed, existing data can be used to model a piece of data that is not captured in soil survey. The piece of soil, site, or climate data extracted from the database undergoes an evaluation in which the estimated data is rated against a curve like that in figure 8-1. These curves have three basic forms: more is better, less is better, or a mid-range concentration is better for an intended use (fig. 8-2). Carbon sequestration or maximizing crop yields are examples of intended uses.

From the evaluation, the rating for a particular property is sent to the corresponding child rule where a rating reason is attached to the membership value. Rating reasons are phrases that describe the nature of the limiting factor, such as "too steep," "floods," "too wet," or "too expansive." Since normally more than one rating makes up an interpretation, the rules are referred to as "child rules" in the U.S. system. The membership values produced by the set of child rules that make up an interpretive model (parent rule) are combined using fuzzy math to produce an overall membership value from 0 to 1 (index number). The final membership value and its associated verbal limitation or suitability rating are assigned in the parent rule.

Figure 8-3 is a diagram of a simplified parent rule for dwellings with basements. The "or" operator dictates that according to the rules of fuzzy math for a limitation style interpretation, the highest membership value from the set of child rules will be returned as the overall rating (index number) for a particular component. The rectangles represent the child rules for the restrictive features. The "and" operator, which returns the lowest of the child rule membership values, is typically used for suitability style interpretations where the least suitable attribute defines how well a soil may function for a land use. Other operators include "mean," "sum," and "product." The operator used in an interpretive model depends on what makes most sense for the system being modeled.

Figure 8-2



Graphs representing the three basic suitability styles. Top.—More is better. In this case, more organic carbon content (kg/square meter) in the upper 30 cm of the soil is better. Middle.—Less is better. In this case, less electrical conductivity (ds/m) in the upper 30 cm of the soil is better. Bottom.—Mid-range is better. In this case, a mid-range average pH in the upper 30 cm of the soil is better.

Limitation Ratings

Soils may be rated according to limitations for soil uses. Limitation ratings typically are based on hazards, risks, or obstructions presented by properties or characteristics of undisturbed soil. The rating consists of a

Figure 8-3

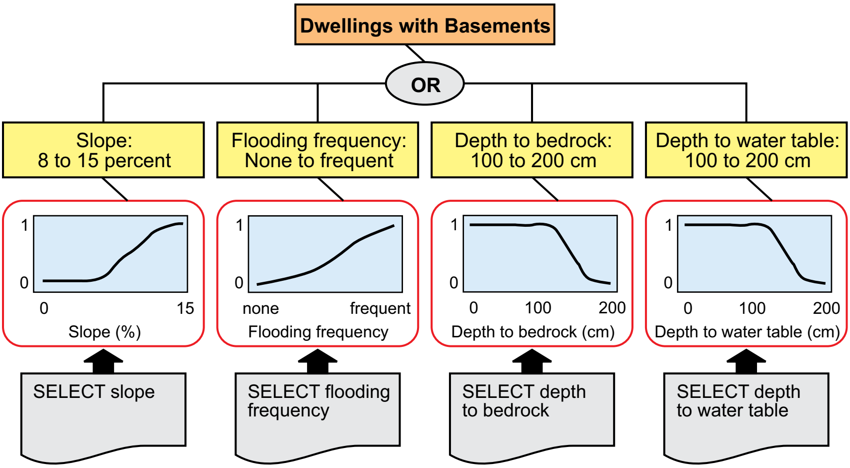


Diagram of a hypothetical parent rule for Dwellings with Basements (a limitation style interpretation).

combination of descriptive terms and membership values that define a soil's membership in the set of soils that have limiting features.

Not limited.—Soils in this interpretive class are not members of the set of soils that have limitations. They are assigned an index number of 0. These soils give satisfactory performance with little or no modification. Modifications or operations dictated by the use are simple and relatively inexpensive. With normal maintenance, performance should be satisfactory for a period of time generally considered acceptable for the use.

Somewhat limited.—Soils in this interpretive class are partial members of the set of soils that have limitations. The membership value is more than 0 but less than 1.0. In this case, the greater the membership value the greater the soil's membership in the set of soils that have limiting features or characteristics. For example, two soils (A and B) have partial membership in the set of soils that are limited and have slope as a restrictive feature. Soil A has a membership index of 0.13 while soil B has a membership index of 0.87. Although both soils have slope as a restrictive feature, soil A is less restricted than soil B. Soils that are partial members of the set of soils that are limited for a specific use do not involve exceptional risk or cost for the specified use. However, they do have certain undesirable properties or features. Modification of the soil itself, special design, or maintenance is required for satisfactory performance over an acceptable period of time. The needed measures typically increase the cost of establishing or maintaining the use, but the added cost is generally not prohibitive.

Very limited.—Soils in this interpretive class are members of the set of soils that are limited for the specified use or management practice. They have an index number of 1.0. These soils, if not appreciably modified, have a high risk for the use. Special design, a significant increase in construction cost, or an appreciably higher maintenance cost is required for satisfactory performance over an acceptable period of time. A limitation that requires removal and replacement of the soil would be rated "very limited." The rating does not imply that the soil cannot be adapted to a particular use, but rather that the cost of overcoming the limitation would be high.

Not rated.—Not rated is a special interpretive class used only when data essential for producing a rating is missing.

Suitability Ratings

Soils may be rated according to the degree of suitability for specific uses. Suitability ratings are based on soil characteristics that influence the ease of using or adapting a soil for a specific use. Suitability ratings also use a combination of descriptive terms (classes) and indexed scoring functions to define a soil's membership in the set of soils that have features or properties that support the intended use or management of the soil. Suitability ratings differ from limitation ratings in that the interpretive model design reports soil features that support the intended application rather than restrictive soil features.

Good.—Soils in this interpretive class are members of the set of soils that have characteristics that sustain the intended use or management practice. They are assigned an index number of 1.0. Satisfactory performance and low maintenance cost can be expected.

Fair.—Soils in this interpretive class are partial members of the set of soils that have characteristics that sustain the intended use. The index number is more than 0 and less than 1.0. In this case, the greater the index value the greater the soil's membership in the set of soils suitable for the use or management practice and the better the soil characteristics. For example, two soils (A and B) have partial membership in the set of soils that are suitable as a source of sand. Soil A has a membership index of 0.27 while soil B has a membership index of 0.78. Although both soils are partial members of the set of soils that are a "fair" source of sand, soil B is better suited. Soils that are partial members of the set of soils that are suitable for a specific use require additional cost because they have certain undesirable properties or features. That cost is generally proportional to the membership index.

Poor.—Soils in this interpretive class are not members of the set of soils that are suitable for the specified use or management practice. They have an index number of 0. These soils have one or more properties that are unfavorable for the specified use. For example, a soil that does not contain sand is rated as a poor source of sand. Unlike other soil limitations, there are no means or treatment for correcting the lack of sand in a soil. In this respect, unfavorable suitabilities generally do not have remedial solutions. Suitability ratings may also be supplemented with the restrictive features that affect soil performance for a specific use. These restrictive features may be a list of soil properties that are important for a specific use and be listed with each class for which they apply. Examples are "fair—water table at depths of 25 to 50 cm" and "poor—bedrock at depths of less than 50 cm." Listing suitabilities with restrictive features in this manner gives the user more complete information by identifying other properties or features that may need treatment for the given use.

Most interpretations designed for general widespread use (such as those used within a large geographic region or a nation) have narrowly defined objectives that can be stated as either limitations or suitabilities. Some users may prefer interpretive expressions that use both approaches, such as a statement of the suitability and also a listing of limiting properties according to severity or difficulty to overcome.

Computer-generated interpretations are commonly made separately for each component in a map unit for any size of area. An aggregated summary rating for each map unit may also be given. Current technologies permit users to map interpretive output for the most limiting component, least limiting component, dominant condition, weighted average, or a specific limiting soil property. Current geographic information systems (GIS) also permit interpretive results to be displayed over broad geographic areas and in a variety of ways, including thematic maps, charts, and standard tables.

Map Units and Soil Interpretations

This section discusses the relationships between the terminology and conventions employed to define and describe map units (see chapter 4) and soil interpretations. The components of map units are the entities for which interpretations are provided. The application of interpretive information to areas of land is through map unit descriptions and depends on an understanding of the map unit concept as it applies to interpretations.

Consociations, Associations, and Complexes

For map units that are *consociations*, the interpretations generally pertain to a single, named soil and are applicable throughout the delineation, although minor components may be rated if the associated data is deemed reliable. For *associations* and *complexes,* the interpretations may be given for each named component as well as the unnamed components or may be given for the map unit as a whole, depending on the objective. In the description of the map unit, information is commonly provided about the geographic occurrence on the landscape of the named components. From this information, interpretations for each of the named components of the map unit may be applied to the portion of the landscape on which it occurs. However, such an application requires information beyond what the soil map alone can provide. The location of each soil within the map unit delineation is needed. The map unit description provides information on the location and extent of each named component of the map unit.

Map units differ in specificity of the named soils and therefore in the broadness of the ranges for various interpretive soil properties. Phases of soil components that are based on series are more specific soil concepts than are phases of soil components that are based on a higher categorical level, such as a great group, e.g., Haplaquods. Consequently, the interpretive information for a phase of a soil component based on soil series has narrower ranges than one based on a higher taxonomic category.

Similar Soils

Similar soils differ so little from the named soil in the map unit that there are no important differences in interpretations. These soils are not named components in the map unit. Recognition is limited to a brief description of the feature or features by which the soil in question differs from the soils in the map unit name. For example: "In places, the upper part of the material is silty clay. In a few areas, the underlying material contains a few lime concentrations."

Dissimilar Soils

Map units are permitted to have certain proportions of included soils that differ sufficiently from the named soil to affect major interpretations.

These soils are referred to as *dissimilar* soils (see chapter 4). Typically, the dissimilarities are such that the soils behave differently. Dissimilar soils are named in the map unit description if they are part of the name of another map unit in the soil survey area. Otherwise, the dissimilar soil is briefly described in a generic fashion, for example, "medium textured soil with bedrock at a depth of less than 50 cm." Location of the dissimilar soils relative to landscape position may be given. Inferences as to the influence of the dissimilar soils on behavior of the map unit may be obtained from their interpretive properties and their location on the landscape. The map unit descriptions may state how the dissimilar soils affect soil behavior. Tabular soil properties and related interpretations do not include properties and interpretations of dissimilar soils. Yield estimates are, in principle, influenced by the occurrence of dissimilar soils if based on field-scale measurement. However, if yields were significantly affected, the dissimilar soil would likely be a named component of the map unit.

For *consociations*, the interpretations pertain to a single, named soil and soils similar to the named soil. Thus, they have a higher possibility of being applicable throughout the delineation than map units named for more than one taxon. For *associations* and *complexes*, the possibility of different kinds of interpretations is higher than for consociations, unless the soils are similar. The interpretations may need to be presented on a probability or possibility basis. Where the soils are related to specific landforms or parts of landforms, interpretations can be related to soils and landforms.

Aggregation

In the context of the modern soil survey database, very few map units are composed entirely of one component; some minor components almost always occur and are interpreted. This presents a challenge for displaying interpretive output in a geographic information system, since only one value can be tied to a polygon. Some method of aggregating the data across components is needed. Depending on the context of the interpretation and what makes sense to display, one of several methods can be used on either the rating classes or the membership values. Historically, for example, the rating class (e.g., slight, moderate, or severe) of the dominant component (component having the highest component percentage) was displayed in either green, yellow, or red for the map unit delineation. For multi-taxa map units, this may represent as little as 40 percent of the map unit area. In the case of multi-taxa map units, a dominant condition aggregation can be used to describe more of the map unit. In this method, the rating class associated with the highest sum of the component percentages is displayed. In some cases, it makes sense to display either the least limiting or most limiting condition for a map unit. It is also possible to reclassify the membership values to make more classes for mapping to represent a gradation of the moderately limited class. If a large proportion of the area of the map unit will be used in the context of the land use, such as in agricultural applications like productivity indices, a weighted average of the membership values by component percentage may be most appropriate. (For additional information, see appendix 4, table A-4.)

Interpretive Soil Properties

Soil survey interpretations are provided for specific soil uses. Interpretations for each soil use are based on a set of interpretive soil properties. These properties include site generalities (e.g., slope gradient), measurements on individual horizons (e.g., particle-size distribution), and temporal repetitive characteristics that pertain to the soil as a whole (e.g., depth to free water).

Abbreviated descriptions for many commonly used interpretive soil properties used in the NCSS are explained below. For logical presentation, they are grouped into categories: site, component, and horizon data; physical features or processes; erosion; and corrosivity. Formal classes have been assigned to several interpretive soil properties. These classes generally are not given unless they are used in field morphological descriptions. All classes are described in the *National Soil Survey Handbook* (USDA-NRCS). Local conditions may dictate other interpretive soil properties or a greater emphasis on a subdivision of some of the interpretive properties here listed.

Site Data

Climate

Mean annual air temperature.—The mean air temperature for the calendar year.

Frost-free period.—The average length of the longest time period per calendar year that is free of killing frost.

Mean annual precipitation.—The mean annual moisture received per calendar year, including rainfall and solid forms of water.

Landscape

Slope.—The range in slope gradient, in percent.

Slope aspect.—The direction in which the slope faces, in degrees.

Slope shape.—Whether the land surface is convex, concave, or linear in the up-down or across planes.

Elevation.—The height above sea level.

Geomorphic component.—The part of the landform the soil occupies (e.g., interfluve, head slope, nose slope, side slope).

Hillslope position.—The position the soil occupies on the landscape (e.g., summit, shoulder, backslope, footslope, toeslope).

Component Data

Field Water Characterization

Available water capacity (AWC).—The volume of water that a soil layer retains between the tensions of 10 kPa (sandy soils) or 33 kPa and 1500 kPa. The water is considered to be available to most common agronomic plants. The amount of water is reduced depending on the volume of rock fragments and the osmotic effects of high salt concentration. Volumes are expressed both as a volume fraction and as a thickness of water. The standard of reference is the *water retention difference* (under 4C in Soil Survey Staff, 2014a). Reductions are made in water retention difference for incomplete root ramification that is associated with certain taxonomic horizons and diagnostic and/or restrictive features (such as fragipans) and for chemical properties that are indicative of root restriction (such as high content of salts, low levels of available calcium, or high levels of extractable aluminum). The amount of available water to the expected maximum depth of root penetration (commonly either 1 or 1.5 m) or to a physical or chemical root limitation, whichever is shallower, has been formulated into a set of classes for root-zone available water storage. For the class sets, the depth of rooting that is assumed and the class limits that are stipulated differ among the taxonomic moisture regimes.

Hydrologic soil groups (HSG).—Interpretive classes that have similar runoff potentials under conditions of maximum yearly wetness. It is assumed that the ground surface is bare and that ice does not impede infiltration and transmission of water downward. In some cases, HSG is used as a soil property.

Flooding.—Inundation by flowing water. The frequency and duration of flooding are placed in classes.

Ponding.—Inundation by stagnant water. The duration and month(s) of the year that ponding occurs are recorded.

Moisture status.—The thickness of the zone with a particular water state, the kind of water state, and the months of year that the water state is present within the soil. Three general water state classes are used in the soil survey database—dry, moist, and wet. Chapter 3 presents more refined classes. In the soil survey database, the wet class is wet-satiated and the moist class includes wet-nonsatiated. Both wet-satiated and wet-nonsatiated are subclasses of wet in chapter 3. There is also a set of classes (see chapter 3) for the occurrence of internal free water. These classes include depth to, kind, and months of the year that a zone of free water is present within the soil. Free water is defined as satiated through saturation.

Horizon Data

Particle Size and Fragments > 2 mm

USDA texture classes and modifiers.—Texture is the relative proportion, by weight, of sand-, silt-, and clay-sized particles (texture classes). The texture classes are modified by adjectival classes based on proportion, size, and shape of rock fragments and by the proportion of organic matter, if the content is high.

Particle-size separates (based on < 2 mm fraction).—The particle-size separates recorded in the soil survey database are percent total sand (2.0–0.05 mm), very coarse sand (2.0–1.0 mm), coarse sand (1.0–0.5 mm), medium sand (0.5–0.25 mm), fine sand (0.25–0.10 mm), very fine sand (0.10–0.05 mm), total silt (0.05–0.002 mm), coarse silt (0.05–0.02 mm), fine silt (0.02–0.002 mm), total clay (< 0.002 mm), and carbonate clay. Percentages are expressed as a weight percent and are based on the < 2 mm fraction. For soils that disperse with difficulty, the total clay percentage is commonly evaluated based on the ratio of 1500 kPa water retention to clay.

Soil fragments > 250 mm (based on whole soil).—This quantity is expressed as a weight percent of the horizon occupied by fragments up to an unspecified upper limit (size of rock fragments does not exceed the size of the pedon). Fragments include pieces of bedrock, bedrock-like material, durinodes, concretions, nodules, and woody materials (organic soils). Fragments larger than 250 mm are not included in the determination of Unified or AASHTO class placements, but they may significantly influence suitability for certain soil uses.

Soil fragments 75–250 mm (based on whole soil).—This quantity is expressed as a weight percent of the horizon occupied by fragments 75–250 mm in size. Fragments include pieces of bedrock, bedrock-like material, durinodes, concretions, nodules, and woody materials (organic soils). The upper fragment size limit cannot exceed the size of the pedon. Fragments greater than 75 mm do not affect the Unified and AASHTO class placements, but they may have a large influence on suitability for certain uses.

Soil fragments > 2 mm (based on whole soil).—This quantity is expressed as a volume percent (whole soil base) of the horizon occupied by the > 2 mm fragments. Associated data include the kind, size, shape, roundness, and hardness of the fragments. Fragments include pieces of bedrock, bedrock-like material, durinodes, concretions, nodules, and woody materials (organic soils).

Percent passing sieve numbers 4, 10, 40, and 200 (based on < 75 mm fraction).—The weight percentage of material passing each sieve. Sieve openings are 4.8 mm (no. 4), 2.0 mm (no. 10), 0.43 mm (no. 40), and 0.075 mm (no. 200) in diameter. Quantities are expressed as a percentage of the < 75 mm material. Material passing the number 4 and 10 sieves may be estimated in the field (see chapter 3) or measured in the office or laboratory. Material passing the number 40 and 200 sieves may be measured directly in the laboratory. Percent passing sieves also may be estimated from USDA particle-size and rock fragment measurements made in the field or laboratory.

Soil Fabric-Related Analyses

Moist bulk density.—The oven-dry weight in megagrams divided by the volume of soil in cubic meters at or near field capacity, exclusive of the weight and volume of fragments > 2 mm.

Linear extensibility percent (LEP).—The linear reversible volume difference of a natural clod between field capacity and oven dryness, inclusive of rock fragments. The volume change is expressed as a percent change for the whole soil. Actual LEP (shrink-swell), in contrast, is dependent on the minimum water content that occurs under field conditions. Organic soils typically do not have reversible volume changes when oven dried. Shrink-swell classes are defined based on LEP.

Water retention (10, 33, and 1500 kPa).—The water content that is retained at 10, 33, and 1500 kPa tension, expressed as a percentage of the oven-dry soil weight inclusive of rock fragments (whole soil). Measurements are conducted in the laboratory on clods (for 10 and 33 kPa tension) and sieved samples (for 1500 kPa tension). Pedotransfer functions are also used to estimate the water content at 10, 33, and 1500 kPa tensions.

Available water capacity.—This is defined in the section “Field Water Characterization” above as the volume of water that should be available to plants if the soil, inclusive of rock fragments, were at field capacity. Field capacity is the volume of water that remains in the soil 2 or 3 days after being wetted and after free drainage becomes negligible. Contents of water are expressed both as a volume fraction and as a thickness of water. Available water is estimated as the amount of water held between 10 or 33 kPa and 1500 kPa tension. Reductions in water retention difference should be made for root-restricting layers that are associated with certain taxonomic horizons and features (such as fragipans) and for chemical properties that are indicative of root restriction (such as low levels of available calcium and high levels of extractable aluminum). Adjustments may also be made for the osmotic effect of high salt concentrations, if present.

Saturated hydraulic conductivity (K_{sat}).—The amount of water that would move downward through a unit area of saturated in-place soil in unit time under unit hydraulic gradient. It is used to convey the rate of water movement downward through the soil under saturated conditions (and unit hydraulic gradient). Saturated hydraulic conductivity classes are defined in chapter 3.

Engineering Classification

Liquid limit (LL) .—The water content at the change between liquid and plastic states. It is measured on thoroughly puddled soil material that has passed a number 40 sieve (0.43 mm) and is expressed on a dry weight basis. Values are typically placed in interpretive classes.

Plasticity index (PI).—The range in water content over which soil material is plastic. The value is the difference between the liquid limit and plastic limit of thoroughly puddled soil material that has passed a number 40 sieve (0.43 mm). The plastic limit is the water content at the boundary between the plastic and semisolid states. Values are typically placed in interpretive classes.

Unified classification.—An interpretive classification system of soil material designed for general construction purposes. It is dependent on particle-size distribution of the < 75 mm, liquid limit, and plasticity index and on whether the soil material has a high content of organic matter. There are three major divisions: mineral soil material having less than 50 percent particle size < 0.074 mm (passing 200 mesh), mineral soil material having 50 percent or more particle size < 0.074 mm, and certain highly organic soil materials. The major divisions are subdivided into groups based on liquid limit, plasticity index, and coarseness of the material more than 0.074 mm in diameter (retained on 200 mesh).

AASHTO classification.—An interpretive classification system of soil material for highway and airfield construction (Procedure M 145-

91; AASHTO, 1997). It is based on particle-size distribution of the < 75 mm fraction and on the liquid limit and plasticity index. The system separates soil materials having 35 percent or less particles passing the no. 200 sieve (< 0.074 mm in diameter) from those soil materials having more than 35 percent. Each of these two divisions is subdivided into classification groups based on guidelines that employ particle size, liquid limit, and volume change. A group index may be computed based on the liquid limit and plasticity index in addition to percent of particles < 0.074 mm. The group index is a numerical quantity based on a set of formulas.

Chemical Analysis

Calcium carbonate equivalent.—The quantity of carbonate in the soil expressed as $CaCO_3$ and as a weight percentage of the < 2 mm fraction. The available water capacity and availability of plant nutrients are influenced by the amount of carbonates, which affect soil pH.

Cation-exchange capacity (CEC).—The amount of exchangeable cations that a soil can adsorb at pH 7.0. Effective CEC (ECEC) is reported in soils where the pH in 1:1 water is 5.5 or less.

Gypsum.—The gypsum content pertains to amount in the < 20 mm fraction. The methods of reference are under 6F (Soil Survey Staff, 2014a).

Organic matter.—Measured organic carbon is multiplied by the Van Bemmelen factor of 1.72 to obtain organic matter content.

Reaction (pH).—The standard method for pH is the 1:1 water extraction. For organic soil materials, the pH in 0.01M $CaCl_2$ is used. Typical agronomic classes are in discussed chapter 3.

Salinity.—A set of classes is used to indicate the concentration of dissolved salts in a water extract. Classes are expressed as electrical conductivity (EC). The measurement of reference is made on water extracted from a saturated paste. Units are decisiemens per meter (dS/m).

Sodium adsorption ratio (SAR).—SAR is evaluated for the water extracted from a saturated soil paste. The numerator is the concentration of water-soluble sodium, and the denominator is the square root of half of the sum of the concentrations of water-soluble calcium and magnesium.

Sulfidic materials.—Upon exposure to air, soil materials that contain significant amounts of reduced monosulfides develop very low pH. The requirements are defined in the latest edition of the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014b). Direct measurement of the pH after exposure to air is also used.

Physical Features or Processes

Depth to Restrictive Horizons or Layers

Depth to bedrock.—The depth to unweathered, continuous bedrock. The bedrock is commonly indurated but may also be strongly cemented, and excavation difficulty is very high or higher (see chapter 3).

Depth to cemented pan.—The depth to a pedogenic zone that is weakly cemented to indurated (see chapter 3). Thin and thick classes are distinguished. The thin class indicates a pan that is less than 8 cm thick if continuous and less than 45 cm thick if discontinuous or fractured. Otherwise, the thick class applies.

Depth to permafrost.—The critical depth is determined by the active layer (the top layer that thaws in summer and freezes again in fall). Utilities, fencing, footings, etc. are placed below the active layer. The minimum depth is affected by depth of annual freezing. Permafrost depth may be strongly influenced by soil cover.

Process Features

Total subsidence.—The potential decrease in surface elevation resulting from the drainage of wet soils having organic layers or semifluid mineral layers. Subsidence may result from loss of water and resultant consolidation, mechanical compaction, wind erosion, burning, or oxidation (of particular importance for organic soils).

Potential frost action.—The likelihood of upward or lateral movement of soil caused by the formation of ice lenses and the subsequent loss of soil strength upon thawing. Large-scale collapse that forms pits is excluded and considered mass movement. Predictions are based on soil temperature, particle size, and pattern of water states.

Erosion

Factors and Groupings Related to Water or Wind Erosion

The K factor.—A relative index of susceptibility of bare, cultivated soil to particle detachment and transport by rainfall. This interpretive factor is used in the Revised Universal Soil Loss Equation (Renard et al., 1997). Measurements are made on plots of standard dimensions. Erosion is adjusted to a standard of 9 percent slope. K factors are currently measured by applying simulated rainfall on freshly tilled plots. Earlier measurements integrated the erosion for the year for cultivated plots under natural rainfall. The K factor may be computed from the composition of the soil, saturated hydraulic conductivity, and soil structure.

The T factor.—The maximum rate of annual soil erosion that will permit crop productivity to be sustained economically and indefinitely (the soil loss tolerance). It can be used in the Revised Universal Soil Loss Equation (Renard et al., 1997). T factors are integer values from 1 through 5 indicating tons per acre per year. The factor of 1 ton per acre per year is used for shallow or otherwise fragile soils, and that of 5 tons per acre per year is used for deep soils that are least subject to damage by erosion.

Wind erodibility groups.—A set of classes, using integer designations from 1 through 8, based on compositional properties of the surface horizon that affect susceptibility to wind erosion. Texture, presence of carbonates, content of iron oxides, materials with andic soil properties, and the degree of decomposition of organic soils are the major interpretive criteria. Each wind erodibility group is associated with a wind erodibility index, expressed in tons per acre per year. The *wind erodibility index* is the theoretical, long-term amount of soil lost per year through wind erosion. It assumes a soil that is bare, lacks a surface crust, occurs in an unsheltered position, and is subject to the weather at Garden City, Kansas (Woodruff and Siddoway, 1965). Tillage frequency and practices are not specified.

Corrosivity

Corrosivity Ratings for Steel or Concrete Structures in Contact with the Soil

Uncoated steel.—This rating depends on soil texture, drainage class, extractable acidity, and either resistivity of a saturated soil paste or electrical conductivity of the saturation.

Concrete.—This rating depends on soil texture, occurrence of organic horizons, pH, and amounts of magnesium and sodium sulfate or sodium chloride in the saturated soil paste.

Dynamic Soil Properties

The previous section dealt almost entirely with soil properties that do not typically change dramatically with use and management. Some soil properties are sensitive to use and management and may change temporally and spatially. These properties are termed dynamic soil properties (DSP) and discussed thoroughly in chapter 9. DSPs are valid and useful as variables in soil interpretations, especially if the outcomes of various management options are being predicted.

Interpretive Applications

In this section, kinds of soil interpretations or groupings of soils are presented. Soil interpretations may be developed at many levels of generalization or abstraction. Commonly, standard interpretations have been developed for wide use and application. Because many soil survey professionals use these interpretive criteria, interpretive results can be consistently produced from place to place. These standard criteria, however, may be too general for applications at some local or regional levels. If appropriate, the standard criteria may provide an effective template from which to adjust interpretive limits or add further criteria to better address local conditions.

Local Relative Placements

The soil properties and model criteria used in making interpretive generalizations are applicable to a very wide range of soils on a regional or national basis. For local decisions, relative rankings within the same interpretive placement may be extremely important. The interpretive model may have to be adjusted to reflect regional or local requirements, legislation, or land use codes. If interpretations are made locally, it is possible to rank soils on a strictly relative basis and to introduce local knowledge about soil behavior that may have been excluded from more general national ratings. The term "local interpretations" is used to describe locally controlled numerical ratings that give relative ranking of soils for a given use. In contrast, the national specific-use interpretive system emphasizes criteria that apply nationwide and thus provides more general rankings.

Local soil interpretations are of greatest value in implementing ordinances for the local planning of specific tracts of land. If comparative ratings of every soil in a specific tract for a particular use are available, then a rational decision can be made whether to proceed, to change plans, or to find another area that has soils with higher potential. In some cases, the best soils in the specific tract for the particular use may be among those with low potential in the soil survey area overall.

The extent to which a given property is limiting and, in many cases, the practices that can be used to overcome the limitation are influenced by other soil properties. An example is the low strength of some soils in coarse-silty families. Such soils may not be limiting for dwelling foundations if the shallowest depth of free water exceeds 2 m. If, however, the shallowest depth of free water is within 25 to 50 cm of the base of the foundation, these soils may be decidedly limiting for foundations. Because the process of determining soil potentials involves input from knowledgeable local people, local interpretations can use more sophisticated criteria.

Steps for Developing Local Interpretations

Local soil interpretations are presented either as a set of qualitative classes, as a numerical index, or as both. The first step is to define the local interpretive product and the information that will be provided to the user. For example, a local sanitary district may request soil interpretations that are based on their sanitary codes. Is the information to be provided as discrete classes or as membership values? Are the coded criteria such that the first requirement can be met or are changes needed? What is the exact intent of each requirement contained in the local code? One requirement may be "depth to water table." What is the local code's definition of water table? What is meant by depth? What months, if any, can the water table be present? Is a layer of near saturation considered a water table for the specified use?

The second step is to identify soil properties that significantly impact or effect the particular use or management of the soil. Critical values for each property are defined locally and are generally based on local code, laws, or administrative regulations, for example, "depth to water table will not be less than 16 inches." Is water table depth of 17 inches significant? Working with the local interpretation sponsor, these and other questions need to be addressed.

The third step is to develop the interpretive model. In this step, the effect of each criterion on the overall rating is described along with the interpretive output. A criterion can be weighted or given precedence over another criterion, or criterion interaction can be described. Once the model is created, extensive testing and a complete technical review are needed before the interpretive products are delivered to the sponsor.

Management Groups

Management groups identify soils that require similar kinds of practices to achieve acceptable performance for an identified use. Historically in the U.S., management groups were limited to uses that involve the growth of plants. Management groups, however, can pertain to both agricultural and nonagricultural uses. The major advantage of management groups is that a user only needs to understand the concepts embodied in a relatively few groups of soils to make management decisions rather than understand and evaluate specific details of all the individual soils in the area. Not all soils in a management group are expected to have identical characteristics or management needs; however, the requirements of each management group must apply to all included soils. Generally, the broader the groups the less specific the descriptions of management needs. The number of classes for a management group depends on the range of soil properties, intensity of use and scale, purpose of the grouping, intended users, and availability of pertinent information. The number of classes must balance the need for homogeneity within a class against the complexity that results from increasing the number. The advantages of management groups are diminished if the classes are so broad that soils within a group differ greatly or so narrow that the number of classes is large and the differences among classes too small.

The most generally applied soil management group in the U.S. is the land capability classification system, which is widely used in the development of conservation plans for farming. Other management groups common in the U.S. are woodland suitability groups, pasture and hayland groups, and ecological sites. Recently, management groups have been defined for purposes of a national soil inventory. Prime farmland, for example, is a kind of management group. Highly integrated generalizations are made for so-called management groups. Groupings of soils may be made for various national land management programs and inventories. These groupings may be highly integrated (such as prime farmland) or be based on a few, quite specific criteria (such as highly erodible lands). Because such interpretive groups are frequently referenced in legislation, their applicability and maintenance have become important in achieving national environmental objectives in the United States. As a result, the official NCSS soil survey database has been designated as the only source of these and other data.

Current U.S. Inventory Groupings

Technical soil groupings have been developed as criteria for application of national legislation concerned with the environment and with agricultural commodity production. Groupings may pertain to agricultural productivity and diversity, erosion potential, quality of surface and ground waters, maintenance of wetlands, or other national needs. Four national groupings are described below: prime farmland, unique farmland, hydric soils, and highly erodible land. Refer to the *National Soil Survey Handbook* to see how various map unit criteria, coupled with interpretive soil properties, have been employed to construct definitions for national inventory purposes.

Prime farmland.—Land that has the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops. It must also be available for these uses. It has the soil quality, growing season, and moisture supply needed to economically produce sustained high yields of crops when treated and managed according to acceptable farming methods, including water management. In general, prime farmland has an adequate and dependable water supply from precipitation or irrigation, favorable temperatures and growing season, acceptable acidity or alkalinity, acceptable salt and sodium content, and few or no rocks. It is permeable to water and air. Prime farmland is not excessively erodible or saturated with water for a long period of time, and it either does not flood frequently or is protected from flooding.

Unique farmland.—Land other than prime farmland that is used for the production of specific high-value food and fiber crops. It has the special combination of soil quality, location, growing season, and moisture supply needed to economically produce sustained high quality and/or high yields of a specific crop when treated and managed according to acceptable farming methods. Examples of crops are tree nuts, olives, cranberries, citruses and other fruits, and vegetables.

Hydric soils.—Soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part. They make up one of three criteria needed for qualification as wetlands.

Highly erodible land.—This land has been defined in order to identify the areas on which erosion-control efforts should be concentrated. The definition is based on erosion indexes derived from certain variables of the Revised Universal Soil Loss Equation (Renard et al., 1997) and the Wind Erosion Equation (Woodruff and Siddoway, 1965). The indexes are the quotient of tons of soil loss by erosion predicted for bare ground divided by the sustainable soil loss (T factor).

Land Use Planning

Land use planning is the formulation of policies and programs for guiding public and private land use in areas of any size where different uses compete for land. The word “land” in this context implies attributes of place and other factors besides soil. Planners must consider place, size of area, relation to markets, social and economic development, skill of the land users, and other factors. Soil surveys can help in land use planning by identifying soil resources in the area and providing information for the evaluation of environmental and economic effects of proposed land uses. They can be interpreted for land use planning through groupings or ratings of soils according to their limitations, suitabilities, and potentials for specified uses.

Local Planning

Local government units, such as those of cities, towns, and counties, do local planning. The planning applies to complexes of farms and ranches, to housing developments, to shopping centers, to industrial parks, and to entire communities or political units.

Local planners use soil interpretations and other information to develop recommendations on alternatives for land use, patterns of services, and public facilities. Planners may need interpretive maps at different scales, depending on their objective. Interpretations of small areas for local planning can rate limitations, identify management or treatment needs, and predict performance and potential of individual kinds of soils identified on detailed soil survey maps. Interpretations of areas that include entire governmental units evaluate soils for all competing uses within the planning area. These maps are smaller in scale, and the map units are associations of soil series or of higher taxa. Local planners commonly need ratings of the whole association for alternative uses. Special maps showing the location of areas having similar potentials or limitations for certain uses may be helpful for planners. Information about amounts and patterns of soils having different potentials within each association can be given in tables or in the text of a soil survey report.

Regional Planning

Geographically extensive soil-limiting factors may pertain to areas that cover several political units. For these situations, regional planning is appropriate. Principal functions of regional planning are collection, analysis, and dissemination of planning and engineering information, preparation of long-range plans, and coordination among the agencies involved.

Most soil maps for regional planning are medium-scale maps generalized from detailed soil survey maps. Soil interpretations show differences between map units in terms of suitabilities and limitations for the principal competing uses. The distribution of map units having similar behavior for a given use is commonly shown on special maps. An accompanying text describes the units, explains the basis for the ratings, and may also describe effects of the pattern of associated soils on the use of specific parcels. Regional planners commonly need information about the suitability of small parcels that is more specific than that provided by generalized soil maps. For example, they may locate an area that is generally good for recreation but also need to know that a potential site for a reservoir has soils suitable for storing water before they can complete the regional plan.

Farmland

Soil surveys in agricultural areas identify soil characteristics that determine suitability and potential of soils for farming. Interpretations for farming involve placement of soils into management groups (such as the land capability classification system) and identification of important soil properties that pertain to crop production, application of conservation practices, and other aspects of agriculture. Other aspects of agriculture include yield potential, susceptibility to erosion, depth to layers that restrict roots, available water capacity, saturated hydraulic conductivity, annual pattern of soil water states (including soil drainage class, inundation, and free water occurrence), qualities that describe tilth, limitations to use of equipment (including slope gradient and complexity, rock fragments, outcrops of bedrock, and stickiness), salinity and sodium adsorption ratio, presence of toxic substances, deficiency of plant nutrients, capacity to retain and release plant nutrients, capacity to retain soluble substances that may cause pollution of ground water, capacity to absorb or deactivate pesticides, and pH as related to plant growth and the need for liming.

The fate of added nutrients and pesticides, as related to farm management and cropping systems, is an important consideration in nonpoint water pollution. Identification of critical soil properties as related to resource management systems is crucial in the wise use of land. The land capability classification system indicates suitability of soils for agricultural uses (Klingebiel and Montgomery, 1961). The system classifies soils for mechanized production of more commonly cultivated field crops—corn, small grains, cotton, hay, potatoes, and field-grown vegetables. It does not apply directly to farming systems that produce crops, such as some fruits and nuts, that require little cultivation or to crops that are flooded, such as rice and cranberries. It also cannot be used for farming systems that depend on primitive implements and extensive hand labor.

Soil productivity.—Soil productivity is the output of a specified plant or group of plants under a defined set of management practices. It is the single most important evaluation for farming. In general, if irrigation is an optional practice, yields are given for both irrigated and non-irrigated conditions. Productivity can be expressed in quantity of a product per unit land area, such as kilograms or metric tons per hectare. For pasture, productivity can be expressed as the carrying capacity of standard animal units per unit area per season or year, or as live-weight gain. Productivity may be expressed as a rating or index related to either optimum or minimum yields, or it may be indexed to a set of soil qualities (properties) that relate to potential productivity. Productivity indices have the advantage of being less vulnerable to changes in technology than expressions of productivity based on yields.

Productivity ratings express predicted yields of specified crops under defined management as percentages of standard yields. They are calculated as follows:

$$\text{Productivity rating} = \frac{\text{predicted yield per unit area}}{\text{standard yield per unit area}} \times 100$$

Such a rating provides a scale for comparing productivity of different kinds of soils over large areas. Ratings lend themselves to numerical treatment. Productivity ratings permit comparison of the productivity of crops having yields that differ markedly in numerical values. For example, a certain soil has a yield of 60,000 kg/ha for silage corn and of 9,000 kg/ha for grain corn. Because these quantities represent similar levels of production, the productivity ratings are similar. Selection of the standard yield of a crop depends on the purpose of the rating. For national comparison, standard yields should be for a high level of management on the best soils of the region for the crop. For potential production, yields under the best combination of practices are used.

Productivity ratings for individual crops can be combined to obtain a general rating for soil over its area of occurrence. Individual ratings are weighted by the fraction of the area occupied by each crop, and a weighted average is calculated that characterizes the general productivity of the soil.

Productivity indices tied to soil properties are used as a relative ranking of soils. Typically, soil properties important to favorable rooting depth and available water capacity are chosen. Some productivity models rely on a few critical soil properties, such as pH and bulk density, to rate soils (Kiniry et al., 1983). The National Commodity Crop Productivity Index (Dobos et al., 2012) uses soil, site, and climatic information to provide an array of the soils of the United States on the basis of their inherent ability to foster crop growth.

Resiliency.—Resiliency of soils is an interpretation that relates to the ability of a soil to rebound from depletion of plant nutrients or organic matter or to rebound from degradation of physical or chemical soil properties (Seybold et al., 1999). Resiliency ratings are based on estimates of the natural fertility of the soil, soil carbon content, available water capacity, favorable rooting depth, particle-size distribution, and distribution of salts in the profile, if present. Resiliency ratings are important in evaluating alternative management systems that are based on lower chemical and energy inputs. Traditional practices that use high inputs of chemical fertilizers and pesticides commonly offset deficiencies in some soil properties that are important to crop production. Resiliency of soils is also important in evaluating long-term effects of management systems on soils.

Rangeland

Rangeland is land on which the historic climax vegetation was predominantly grasses, grass-like plants, forbs, or shrubs as the consequence of a dry climate. It includes land revegetated naturally or artificially to provide a plant cover that is managed like native vegetation (introduced forage species are also managed as rangeland). The vegetation is suitable for grazing and browsing by animals. Rangeland includes natural grasslands, savannahs, many wetlands and deserts, tundra, and certain shrub and forb communities.

Soil-ecological site correlation within a soil survey gives the suitability of the soil to produce various kinds, proportions, and amounts of plants. This knowledge is important in developing management alternatives needed to maintain site productivity. Rangeland interpretations in the U.S. are normally produced as ecological site descriptions.

Ecological site descriptions (ESD).—An ESD commonly contains the following information:

1. Physiographic features that describe the position of the site on the landscape and whether the site generates or receives water runoff.
2. Climate factors that typify the site, as well as characterize the dynamics of the site, including storm intensity, frequency of catastrophic storm events, and drought cycles.
3. Influencing water features where the site is associated with wetlands or streams.
4. Representative soil features that significantly affect plant, soil, and water relationships and site hydrology, such as major soil families, geologic formation, soil surface features, surface horizon and texture, soil depth, thickness and available water capacity of major root zone, kind and amount of accumulations, rock fragments in the profile, reaction, salinity, sodicity, soil water states, water table, and flooding.
5. Plant communities of the site, including a description of the vegetation dynamics, the common vegetative states of the site, and the transitions between states. Thresholds are identified as boundaries of the vegetative states. Other plant community information includes a state-and-transition diagram, plant community composition, ground cover and structure, annual production, growth curves, and photos of each vegetative state (see appendix 4).

6. Site interpretations for the animal community (livestock and wildlife), hydrologic functions, recreational uses, wood products, and other potential uses.

Forestland

Forestland is land dominated by native or introduced trees with an understory that commonly consists of many kinds of woody plants, forbs, grasses, mosses, and lichens. Some forest communities produce enough understory vegetation to provide forage.

Soil-ecological site correlation within a soil survey gives the suitability of the soil to produce wood products or other ecosystem services. If forestland is part of a soil survey, estimated productivity of the common trees is given for each individual soil. The understory vegetation is described at the expected canopy density most representative of the site. Determination of the soil's productivity requires close collaboration between foresters and soil scientists.

Wood production or yield is commonly expressed as the *site index* or as some other measure of the volume of wood produced annually. Site index is the average height of dominant and codominant trees of a given species at a designated age. Measurements of site index are typically extended to several similar soils for which data are unavailable. The site index is correlated to each soil and may be further interpreted in terms of cubic meters per hectare.

Soils may be grouped using the *woodland ordination system*. This system uses symbols to indicate productivity potential and major limitations for the use and management of individual soils or groups of soils. The first part of the ordination symbol, a number, is the class designator. It denotes potential productivity in terms of the nearest whole cubic meter of wood growth per hectare per year for the soil, based on the site index of an indicator tree species. For several species, data are available for converting site index to average annual wood growth. The second part of the ordination symbol (the subclass) indicates soil or physiographic characteristics that limit management—stoniness or rockiness, wetness, or restricted rooting depth. The ordination symbol may also have a third part to distinguish groups of soils that respond similarly to management. Soils with the same group symbol have about the same potential productivity, are capable of producing similar kinds of trees and understory vegetation, and have similar management needs.

Soils may be rated for such factors as susceptibility to mechanical compaction or displacement during forestry operations, limitations due to burning, hazards from soil-borne pests and diseases, and limitations due to specific soil properties such as wetness. In the management of trees, one must first understand the soil on which the trees grow or are to be grown. Soil surveys include information that can be used effectively in the management of forestland. This information includes:

Erosion hazard.—The possibility that erosion damage may occur as a result of site preparation and the aftermath of cutting operations, fires, and overgrazing.

Equipment limitations.—Limits on the use of equipment either seasonally or year-round due to soil characteristics such as slope, surface rock fragments, wetness, and surface soil texture.

Seedling mortality.—A rating that considers soil properties that contribute to the mortality of naturally occurring or planted tree seedlings, such as droughtiness, drainage class, and slope aspect. It does not consider plant competition.

Windthrow hazard.—A determination based on soil properties that affect the likelihood of trees being uprooted by wind as a result of insufficient depth of the soil for adequate root anchorage. A fragipan, bedrock, gravel, or high water table may affect soil rooting depth. Differences in root systems related to tree species are not considered. The rating is typically independent of the probability of high winds unless the soil is typically in landscape positions susceptible to high winds.

Plant competition.—The likelihood of invasion or growth of undesirable plants in openings within the tree canopy. Depth to the seasonal water table and available water capacity are the soil properties having the greatest effects on natural regeneration or suppression of the more desirable plant species.

Windbreaks

Windbreaks are made up of one or more rows of trees or shrubs. Well placed windbreaks of suitable species protect soil resources, control snow deposition, conserve moisture and energy, beautify an area, provide wildlife habitat, and protect homes, crops, and livestock. The plant species used in windbreaks are not necessarily indigenous to the area. Because each tree or shrub species has certain climatic and physiographic limits, a particular species may be well suited or poorly suited based on soil characteristics. Therefore, correlation of soil properties and adaptable windbreak species is essential.

A listing of adaptable species is given for each kind of soil, or grouping of soils by ecological site or suitability group, where windbreaks can serve a useful purpose—such as open field-planting, interplanting in existing woodland, and environmental modifications like wind or water barriers and development of wildlife habitat. The plant species identified for these purposes are grouped by height classes at 20 years of age.

Recreation

Interpretations in urban and suburban areas are made for golf fairways, picnic sites, playgrounds, paths, trails, and campsites. Interpretations for ski slopes, snowmobile trails, and off-road vehicles are made in some places. Ratings are typically based on restrictive soil interpretive properties, such as slope, occurrence of internal free water, texture of surface horizons, and soil resiliency.

Interpretations for recreation must be applied cautiously. Many recreational areas in the U.S. that are on large tracts of publically owned lands have only order 3 or higher soil surveys. Map units for such soil surveys are commonly associations or complexes of soils that may differ markedly in their limitations and suitabilities. Furthermore, general suitability of the map unit must take into consideration not only the qualities of the individual kinds of soil but also the soil pattern and potential interactions. Suitability may depend on a combination of several kinds of soil in a pattern appropriate to the intended use. Finally, factors other than soils are important in recreational planning. Aesthetic considerations, accessibility, land values, access to water and public sewer lines, presence of potential impoundment sites, and location relative to existing facilities may be important even though none of these factors is evaluated for map units.

Wildlife Habitat

Soils influence wildlife primarily through control over vegetation diversity. Descriptions of the soil as wildlife habitat have two parts. In one part, suitability class for different vegetation groups is recorded. These vegetation groups are called habitat elements. Each habitat element is a potential component of the environment of wildlife. Hardwood trees and shallow water areas are examples of habitat elements. In the other part of the description, soils are rated separately for several kinds of wildlife, including animals adapted to openland, woodland, wetland, and rangeland. Current land use and existing vegetation are not considered because these factors are subject to change and cannot be determined from a soil map. Wildlife population is also not considered because of the mobility of wildlife and the possibility of changes in population during the year. The ratings show where management for wildlife can be applied most effectively and which practices are appropriate. The ratings may also show why certain objectives (e.g., the production of pheasants) may not be feasible. Some soil surveys include explicit management recommendations.

Construction Materials

Soil survey interpretations estimate suitability of the soil as construction material and show where to locate material that can be mined. Material that compacts readily and has high strength and a low shrink-swell potential is preferred as base material for roads and foundations. Material for fill has to be evaluated for the potential for acid-sulfate formation, which can corrode steel and concrete and form unfavorable pH conditions for lawns and landscaping. Gravel and sand are used for concrete, road surfacing, and filters in drainage fields. Organic soil material is used widely as horticultural mulch, potting soil, and soil conditioner. Mineral soil is generally rich in organic matter and is applied to lawns, gardens, and roadbanks. Soils can be rated as probable sources of these materials. The quality of a particular site, however, typically cannot be specified.

Building Sites

Interpretations are made for construction of small buildings; for installation of roads, streets, and utilities; and for establishment of lawns, landscaping, and stormwater management. Such soil uses involve high capital expenditures in relatively small areas. Onsite evaluation typically is necessary.

Soil survey interpretations are useful for comparing alternative sites, in planning onsite investigations and testing, and in land use planning. Soil maps can assist in selecting building sites that are near areas suitable for utilities, parks, and other needs.

The preparation of building sites may alter soil properties markedly. As a result, some interpretive soil properties for the undisturbed sites must be applied cautiously. Upper horizons may have been removed and locally translocated, and the depth to horizons important to soil behavior may have been increased or decreased. The pattern of soil water states may have changed. Areas may have been drained and, therefore, are not as wet as indicated in the survey. Irrigation may have been used to establish and maintain vegetation and resulted in a more moist soil and deep movement of water. Pavements, roofs, and certain other aspects of construction increase runoff and may cause inundation at lower elevations where such hazards are not indicated in the survey.

Building construction.—Construction and maintenance of buildings belongs primarily to the fields of architecture and engineering.

Additionally, large multistory structures are generally supported by footings placed below the depth of soil survey examination. Therefore, soil survey interpretations are not a definitive source of information for building construction. Important interpretive soil properties for small buildings and accessory installations, such as roads and utilities, include slope, inundation, mass movement, potential frost action, depth to bedrock and cemented pans, shrink-swell potential, rock fragments > 75 mm, erodibility, subsidence, and soil strength.

Roads, streets, and utilities.—Performance of local roads and streets, parking lots, and similar structures is directly related to performance of the underlying soil in many cases. Pipelines and conduits commonly are buried in soil at shallow depth. Soil properties may affect cost of installation and rate of corrosion. Soil material is used directly as topsoil, roadfill, and aggregate for concrete. Soil interpretations can predict some suitabilities and limitations of different kinds of soil for these uses, although they cannot predict performance of highways, major streets, and similar structures. For these structures, onsite testing is necessary. Use of soil survey information, however, may reduce the number of borings and engineering tests needed.

Soil information in conjunction with engineering testing can identify soils that can be stabilized in place for a road base and establish where gravel or crushed stone will be needed. Soil surveys can be helpful in deciding methods of stabilizing cuts and fills. Soil properties may affect the cost of installation and length of service of buried pipelines and conduits. For example, shallow bedrock greatly increases the cost of installation. Rate of corrosion is related to wetness, electrical conductivity, acidity, and aeration. Differences in properties between adjacent horizons, including aeration, increase corrosion in some soils. Soil properties affect the cathodic protection provided by sacrificial metal buried with pipes. Rock fragments can break protective coatings on pipes. Shrinking and swelling of some soils may preclude the use of certain kinds of utility pipe.

Soil survey interpretations may be particularly useful in the prediction of potential problems along proposed routes. Hydrologic information and other data combined with interpretive soil properties, such as hydrologic groups, can be helpful in estimating potential runoff for designs of culverts and bridges. The probability of bedrock and unstable soils that require removal or special treatment can be determined from soil surveys.

Lawns and landscaping.—Soil survey interpretations give general information about sources of fill and about planning, planting, and maintaining grounds, parks, and similar areas. Particularly important are the suitability of the soil for turf, ornamental trees, and shrubs; the ability to withstand trampling and traffic; the suitability for driveways and other surfaced areas; and the ability to resist erosion. A number of soil chemical properties may be critical, especially for new plantings. Interpretations for particular plants and the treatments for a specific site require input from other disciplines.

Many lawn and ornamental plantings are made in leveled areas on an exposed subsoil or substratum or on excavated material that has been spread over the ground. Interpretations can be made for the suitability of such soil materials for lawns and other plantings, the amount of topsoil that is necessary, and other treatments required for satisfactory establishment of vegetation. Highway departments use soil interpretations when establishing and maintaining plantings on subsoil material in rights-of-way.

Stormwater management.—Building of infrastructure (such as roads, sidewalks, and rooftops) creates impervious surfaces, which greatly increase runoff and can contribute to flooding. Soils can be interpreted for various practices for stormwater retention and infiltration that can reduce the threat of flooding and the pollution of surface waters. The ability of the soil to transmit water and retain harmful materials while not contributing to landscape instability are important site considerations.

Waste Disposal

Waste disposal practices either place the waste in a relatively small area of soil or distribute the waste at low rates over larger areas.

Localized placement.—In this context, waste includes a wide range of material, including household effluent, solid waste, and industrial wastes of various kinds. Effluent from septic tanks is distributed in filter fields. Liquid wastes are stored and treated in lagoons constructed in soil material. Solid wastes are deposited in sanitary landfills and covered with soil material.

Extremes in saturated hydraulic conductivity and free water at a shallow depth limit the use of soil for septic tank absorption fields. (Table 8-1 shows the criteria for septic tank absorption fields.) Sewage lagoons require a minimum saturated hydraulic conductivity to prevent rapid seepage of water, a slope within certain limits, and a slight or no possibility of inundation or the occurrence of free water at shallow depths.

Soils are used to dispose of solid wastes in landfills, either in trenches or in successive layers on the ground surface. For trench disposal, properties that relate to the feasibility of digging the trench (i.e., depth to bedrock and slope) and factors that pertain to the likelihood of pollution of ground water (i.e., shallow zone of free water, inundation occurrence, and moderate and high saturated hydraulic conductivity) have particular importance. For disposal on the soil surface, saturated hydraulic conductivity, slope, and inundation occurrence are important.

Low-intensity distribution.—Soil is used to render safe either solid or liquid waste that is spread on the ground surface or injected into the soil. This waste includes manures, sewage sludge, and various solids and wastewaters (particularly from factories that process farm products). In general, the physical process of distribution is limited by steep slopes, rock fragments > 75 mm, rock outcrops, and wetness. The rate at which wastes can be applied without contaminating ground water or surface water is called the "loading capacity." Low infiltration values limit the rate at which liquid wastes can be absorbed by soil. Similarly, low saturated hydraulic conductivity through most of the upper meter limits the rate at which liquid wastes can be injected. Shallow depth of a hardpan or bedrock or coarse particle size reduces the amount of liquid waste that a soil can absorb in a given period. The time that wastes can be applied is reduced by frozen soil or occurrence of free water at shallow depths. Low soil temperatures reduce the rate at which the soil can microbiologically degrade the material.

Soils differ in their capacity to retain pollutants until they are deactivated or used by plants. Highly pervious soils may permit movement of nitrates to ground water. Similarly, saturated or frozen soils allow runoff to carry phosphates absorbed on soil particles or in waste deposited on soil directly to streams without entering the soil. Soils that combine a limited capacity to retain water above slowly permeable layers and a seasonal water excess may allow water that is carrying pollutants to move laterally at shallow depths. Such water may enter streams directly.

Large quantities of waste may change the soil. Heavy loading with liquid waste may reduce the oxygen supply so that yields of certain crops decrease. Conversely, heavy loadings can provide beneficial irrigation and fertilization for other kinds of soil and crop combinations. Animal wastes improve most soils, but effects differ according to the kind of soil.

Typically, the first step in making soil interpretations for disposal of wastes is to determine how disposal systems for each kind of waste have performed on specific kinds of soil in the area. Data may come from practical operations or from research. Which properties are critical and how to appraise the effects of the properties need to be determined. Limiting values of critical properties can be determined through experience and may be used in making interpretations where data on soil performance are scarce or lacking.

Water Management

Water management, as discussed here, relates to construction of relatively small- or medium-sized impoundments, control of waterways of moderate size, installation of drainage and irrigation systems, and control of surface runoff to minimize erosion. These activities may require large capital expenditures. In most cases, onsite evaluation should be conducted, particularly for soil properties at depth. Order 2 or order 3 soil surveys can be helpful in evaluation of alternative sites, but onsite investigations are required to design engineered projects.

Ponds and reservoirs.—Soil information is used in predicting soil suitability for ponds and reservoir areas. Impoundments contained by earthen dikes and fed by surface water have somewhat different soil requirements than those that are excavated and fed by ground water. Separate interpretations are commonly made.

Soil seepage potential, as determined by the minimum saturated hydraulic conductivity and the depth to pervious soil material, is an important factor for design of ponds and reservoirs. Slope is also important because it affects the capacity of the reservoir. The soil's hydrologic group (see chapter 3) pertains to the prediction of runoff into a pond or reservoir.

Embankments, dikes, and levees.—These are raised structures made of disturbed soil material constructed to impound water or to protect land from inundation. Soils are evaluated as sources of material for construction. Particle-size distribution and placement in the Unified system are important considerations. Interpretations do not consider whether the soil in place can support the structure. Performance and safety may require onsite investigation to depths greater than are typically considered in a soil survey.

Irrigation.—Important considerations for the design of irrigation systems are feasible water application rates, ease of land leveling and the resultant effect on the soils, possibility of erosion by irrigation water, physical obstructions to use of equipment, and susceptibility to flooding. An order 1 soil survey may be needed for observations and measurements of infiltration rates at depths greater than typically surveyed. The interpretations may be based on various soil properties, including saturated hydraulic conductivity, available water capacity, erodibility, slope, stoniness, effective rooting depth, salinity, sodium adsorption ratio (SAR), gypsum content, and other properties that may affect the level of crop response.

Interpretations for irrigation in arid and semiarid regions may be more complex than in humid regions, because irrigation changes the soil water regime more in arid and semiarid areas. Salinity and SAR of soils can be particularly significant, as can the quality of irrigation water. In arid and semiarid areas, small differences in slope and elevation can lead to an accumulation of salt-laden drainage water in low places or to development of a high water table if a proper drainage system is not provided.

Drainage.—Drainage refers to the removal of excess water from soils for reclamation or alteration. Engineers establish the criteria for drainage construction. The criteria include spacing and depth of subsurface drains, depth and width of open ditches and their side slopes, and allowable gradient. Soil properties important to drainage include water transmission, soil depth, soil chemistry, potential frost action, slope, and presence of rock fragments > 75 mm.

Public Health and Safety

Soil and site properties can profoundly influence the distribution of pathogenic organisms, the risk of mass movement and earthquake-induced hazards, and disease vectors related to mosquito habitat. The suitability of soils as habitat for soil-borne fungi and bacteria that affect human or animal health may be determined with increased resolution of maps showing various hazards and propensities of soils at soil survey scales.

Soil-Borne Diseases

Valley Fever is an example of a soil-borne disease. It is caused by the fungi *Coccidioides immitis* and *Coccidioides posadasii*. Because these fungi have very specific soil and climate requirements, areas that are suitable as habitat for these organisms can be predicted. Therefore, areas of likely habitat can be avoided or measures can be taken to prevent creating dust during times that the fungi are releasing spores.

Mass Movement

The likelihood of soil slippage using shear strength and shear stress concepts can be inferred from the slope, land surface shape, and soil depth to planes of weakness. The propensity of some soils to liquefy during earthquake events is influenced by the age and wetness of the landscape. These attributes and their relationships can be modeled using soil survey data. Care is needed in evaluating the relevance of the predictions if the depth of inference for the soils data is not deep enough to characterize the affected soil material.

Geophysical Tools and Site Suitability

Ground-penetrating radar (GPR) and other geophysical tools (discussed in chapter 6) are widely used for locating underground infrastructure, soil features, and burial sites and other applications in which large areas must be investigated without disturbing the soil. Soil properties such as electrical conductivity, clay content, and mineralogy influence the attenuation and penetration of electromagnetic energy. Where and how well GPR will work can be predicted using soil properties. The U.S. has developed a series of interpretive maps illustrating soil suitability for GPS use throughout the country (USDA-NRCS, 2009).

Subaqueous Soils

Subaqueous soils form in water-deposited material and can be mapped, characterized, and interpreted like terrestrial soils. These deposits undergo pedogenic processes (Demas and Rabenhorst, 2001). They occur in predictable patterns and have predictable soil properties that are useful for interpretation. This section discusses some soil interpretations that have been developed for subaqueous soils in the United States. Chapter 10 provides more information on the nature and properties of subaqueous soils. Because land use does not end at the water's edge, interpretations have been developed for the subaqueous environment. Mapping and characterizing subaqueous soils helps ensure the wise use of the near offshore soil resource. Below are a few examples of interpretations for subaqueous soils.

Moorings

A stable place to tie up watercraft is essential during a storm. The type of mooring that can be used for securing watercraft depends on the nature of the subaqueous soil (Surabian, 2007). In areas where the bottom is fluid (soft bottom), a mushroom anchor will suffice to hold the vessel in place. In areas where the bottom is composed primarily of sand and gravel (hard bottom), a deadweight anchor is needed.

Eelgrass Restoration

Eelgrass is an important species in the subaqueous environment because it supplies food and cover for desirable fish and shellfish. It requires a sandy soil matrix free of reduced monosulfides. The water column must be shallow enough to allow light penetration but deep enough to avoid freezing.

Land Disposal of Dredged Material

Sediment is removed from navigation channels to facilitate the movement of vessels. If this material is placed on land, it will oxidize in the subaerial environment. If reduced monosulfides are present in the dredged material, these compounds will oxidize and form sulfuric acid, which can have severe environmental effects.

Hard Clam Substrate

Aquaculture is an important agricultural sector in coastal areas. Hard clams require a sandy substrate since fine soil particles can clog their filtering apparatus.

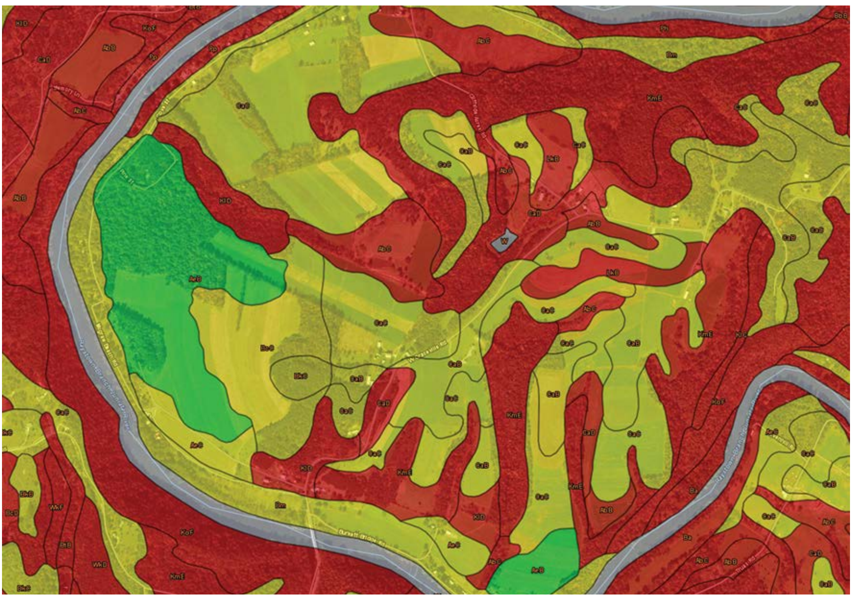
Areal Application of Interpretations

The objective of soil surveys is to provide interpretations for areas delineated on soil maps. This section discusses the relationship of interpretations to map unit terminology and conventions (described in detail in chapter 4), the interpretive basis of map unit design, and the uncertainty of interpretive predictions for specific areas within the map unit.

Polygon-Based Soil Interpretations

Polygon-based interpretations are applied uniformly to an entire map unit delineation. The top image in figure 8-4 is a soil map that shows the delineations of map units and depicts other features on the landscape. The bottom image in figure 8-4 shows the same area as the top image and illustrates the ratings of the soil map units for local roads and streets. Green indicates not limited, yellow somewhat limited, and red very limited. Gray areas are not rated because there were not enough data to derive a rating (in this case they are water bodies). Table 8-3 indicates which soil properties (in the column “Rating reasons”) are limiting for local roads and streets for the Albrights map unit (AbB). The numeric values give an estimate of the degree of limitation posed by each reason. Note that even though one component is given in the map unit name (i.e., Albrights), it is understood that more than one component exists in the map unit. In this case, the included Brinkerton soil is estimated to make up about 5 percent of the map unit (listed in the column “Component name”).

Figure 8-4



Soil map (top) showing the distribution of mapping units on the landscape and interpretive map (bottom) showing limitations for local roads and streets.

Table 8-3

Limitation Ratings for Local Roads and Streets for the Albrights Map Unit (AbB)

Local Roads and Streets—Summary by Map Unit—Bedford County, Pennsylvania (PA009)						
Map unit symbol	**Map unit name**	**Rating**	**Component name** *(percent)*	**Rating reasons** *(numeric values)*	**Acres in AOI**	**Percent of AOI**
AbB	Albrights silt loam, 3 to 8 percent slopes	Very limited	Albrights (90%)	Depth to thick cemented pan (1.00)	43.6	3.1%
				Depth to thin cemented pan (1.00)		
				Frost action (0.50)		
				Depth to saturated zone (0.48)		
			Brinkerton (5%)	Depth to thick cemented pan (1.00)		
				Depth to saturated zone (1.00)		
				Depth to thin cemented pan (1.00)		
				Frost action (1.00)		
				Low strength (1.00)		

Raster-Based Soil Interpretations

The processes used in digital soil mapping (see chapter 5) present intriguing possibilities for the future development and display of spatially explicit soil interpretations. The current U.S. interpretation system has two primary shortcomings that limit the precision and accuracy of the derived predictions. First, the system is constrained to use only data from within the database. While this is reasonable for the soil attribute data, ideally climatic and geomorphic data would be obtained from more authoritative sources. Second, the interpretive output can only be displayed as aggregated values for the polygons of the original mapping. Any fine detail of the landscape cannot be represented. Digital soil mapping (DSM) offers the opportunity to overcome both of these limitations by allowing the use of authoritative data layers and displaying results at the resolution of the digital soil map. The interpretive models themselves are generally scale-independent, and higher resolution input data would allow greater confidence in the spatial location of the results.

The advantages of raster-based interpretations relate to the scale of the land use. Land uses such as farming, ranching, and forestry are relatively extensive operations (10 to 1,000 hectares) with a relatively low investment per hectare (although some farming systems are more intense than others). For these uses, a scale of 1:20,000 may be adequate. Other land uses, such as homesites and animal waste facilities, are on a more intensive scale (0.1 to 1 hectare) and have a higher monetary investment per hectare. They occupy a discrete portion of the landscape, which may fall into an area that is not accounted for on an aggregated 1:20,000 soil map. A linear land use, such as a pipeline or road, may involve a long, narrow segment of the landscape that encompasses several kilometers of length and traverses portions of many map units. Accounting for the inherent homogeneity of the landscape for these types of land use could allow routing the right-of-way to avoid obstacles and sensitive areas that might not be displayed on a soil map.

In a raster environment, continuous soil data would allow depiction of interpretive results limited only by the pixel size of the DSM. Environmental covariates, such as climate and topographic data, as well as the soil attribute data would be processed by the interpretation modeling system for each pixel (fig. 8-5). These data would already be available from the DSM process.

Spatially explicit raster-based interpretations would be subject to the same issues of data quality and confidence as the DSM from which it was derived. The confidence level would be indicated in the DSM, and the interpretive results would also have a reportable confidence interval. The processing workload would be much larger than what is currently needed and would vary depending on the resolution of the DSM.

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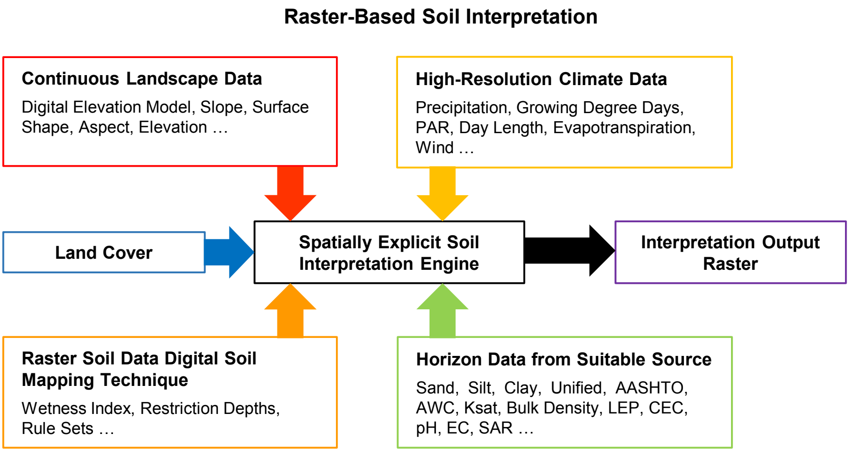
Figure 8-5



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CHAPTER 9

Assessing Dynamic Soil Properties and Soil Change

By Skye Wills, Candiss Williams, and Cathy Seybold, USDA-NRCS.

Dynamic soil properties (DSPs) are properties that change with land use, management, and disturbance over the human time scale (decades to centuries). In contrast, inherent soil properties (e.g., soil texture) change little, if at all, with changes in land use and management. The term "dynamic soil properties" was used by Tugel et al. (2005) to describe soil properties that can be documented as a part of soil survey activities. The procedures for measuring and recording DSPs were later outlined in the *Soil Change Guide* (Tugel et al., 2008). The term DSPs has gained common usage among soil scientists when referring to properties that can be changed intentionally or inadvertently through human land use and management, either directly (as through tillage) or indirectly (as through causing acid rain). While many soil properties (such as moisture, temperature, and respiration) are dynamic on daily, or smaller, time scales, information about them is not included in current soil survey products. The DSPs addressed by soil survey include properties that reflect soil functions and can serve as indicators of soil quality (or health) or indicators of ecosystem services. Dynamic soil properties are more pronounced at or near the soil surface and can be used to evaluate changes and departure from a benchmark or set of reference soil properties. Conceptually, this allows DSPs to be correlated with map unit components used in traditional soil survey (see chapter 4).

Importance of DSPs

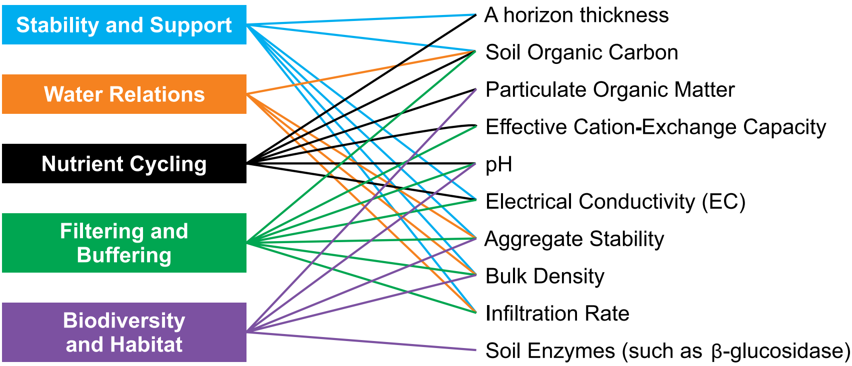
Many land and water conservation programs in the U.S. depend upon management of dynamic soil properties. Proven conservation practices are used to maintain the soil's productivity, health, and long-term sustainability. Conservation planning relies on the knowledge of the current state of the soil resource and what is achievable through conservation practices. DSP assessments provide a range of potential soil property values that define what is achievable.

DSP data is used to document, explain, and predict the effects of land use and management on soil and ecosystem functions. It is collected in a way that documents both soil properties and classifications along with information on land use and management, then stored in an organized database. Information about past and current land use and management can be used to explain current soil properties. It can also be used, through inference or modeling, to predict future soil properties and functions.

Soil function is a way of describing the role of soil in the environment and has been used to define the concept of soil quality and soil health. Essential soil functions include nutrient cycling, water storage and release, biodiversity and habitat, filtering and buffering, and physical stability and support (simplified from Mausbach and Seybold, 1998). Soil stores and moderates the cycling of nutrients and other elements. It regulates the drainage, flow, and storage of water and solutes (N, P, and pesticides). It supports biodiversity and habitat and promotes the growth of plants, animals, and microorganisms. It serves as a filter and buffer for toxic compounds and excessive nutrients and protects the quality of water, air, and other resources. It provides physical stability and support, allowing the passage of air and water through its porous structure, serving as a medium for plant roots, and providing an anchoring support for human structures. While many soil functions are complex and difficult to measure, some key soil properties can be considered indicators of specific soil functions (fig. 9-1) (Doran et al., 1996; Karlen and Stott, 1994; Mausbach and Seybold, 1998). These indicator properties are the focus of soil survey DSP collection.

The framework of soil survey offers an opportunity to collect and disseminate information about how DSPs (and the soil functions they support) change with vegetation, land use, and management across space and time (Wills et al., 2016). DSP data, such as bulk density values under various grazing schemes, enhances soil survey information by providing soil property potentials under various land use and management scenarios. By combining DSP information with spatially linked soil survey information (e.g., soil map unit components), soil survey provides spatial context (maps, areas affected, etc.) to land users, researchers, and decision makers regarding the expected impacts of changes in land use and management. Soil property and function potentials along with collated DSP datasets provide greater specificity of soil interpretations, target values for soil quality and health assessment, guidelines for indicator monitoring, and data for calibration and validation of resource modeling.

Figure 9-1



Relationship between soil functions and some dynamic soil properties (modified from Tugel et al., 2008).

How to Collect DSPs for Soil Survey

DSP projects organize data collection and analysis around specific soils, soil groups, and land management systems. The scope, specificity, and replication of each DSP project depend on the goals for that project. The overarching goal of data collection in a DSP project is to document the range and central tendencies of DSPs for a given set of soils and land management conditions (such as reference and degraded states or best and typical crop management practices). The project should provide information about typical and potential DSP values for soil map unit components and ecological site descriptions. With adequate replication, these projects can be conducted as soil change comparison studies (Tugel et al., 2008) in which alternate conditions are used in a space-for-time substitution framework to make inferences about how soils have changed over time under specific management scenarios. In this approach, all places with the same soil (or group of soils) are assumed to have had the same properties at time zero (i.e., before the specific land management practices were applied). The assumption is that any differences observed are due to management and not inherent spatial variability. Multi-scale replication limits the influence of any spatial variability observed when making conclusions about soil change. DSP projects may also seek to document baseline conditions (such as ecological site reference conditions), best and worst case management scenarios, or alternate conditions of interest.

DSP information for soil survey must be collected, organized, and used in a way consistent with the soil survey protocols and standards used for inherent properties. Data collection for soil survey can be characterized in two ways: dispersed and project based. *Dispersed* DSP data collection refers to the integration of DSP data collection with other routine soil survey project operations. As a result, DSP and land management information is documented throughout a wide range of soil survey activities. Efforts are not concentrated on any single land use or management system but are dispersed throughout all situations in which the soil occurs. In contrast, *project-based* DSP data collection is designed to intensively evaluate specific land management conditions. The most robust DSP data collection includes both approaches and so provides both spatial and land management representation (from dispersed efforts) and detailed comparisons of management scenarios in specific soil landscapes (from project-based efforts). DSP data can be used to evaluate the soil data representativeness (across land use and management systems) and assess spatial variability.

The goal of dispersed DSP collection is to build on other soil survey activities and increase the general knowledge of DSPs across all soils and land management conditions. In this context, "land management condition" is a general term that captures a range of possible situations, including ecological states and vegetative communities, land use, and specific crop and pasture management systems. Advantages of dispersed data collection are that it requires little additional resources and provides information on a wide range of soils and conditions to managers, modelers, and policy makers. Analysis of this data can be used to group soils and land management conditions for further evaluation through DSP projects. It can also be used to validate summaries and predictions made from completed projects.

Dispersed DSP Data Collection

At the location of each observation, it is important to record, at minimum, information on the site, pedon, and land management condition and practice. This data includes any known information about general land use, ecological state, type and amount of vegetation, and cropping systems; e.g., tillage, crop rotation, and pesticide or fertilizer applications. Additional soil properties may be assessed on samples near the soil surface, e.g., enzyme activity and aggregate stability. Procedures and terminology for recording this information should be standardized. Robust soil information systems include data elements related to indicators of soil function and land use and management condition.

Project-Based DSP Data Collection

Project-based DSP data collection requires thorough planning and typically is the most intense type of data collection. The type of project determines how data collection will proceed. Projects can be planned to meet multiple project goals. Site and pedon replication should be planned to meet all project goals on the smallest unit of soil and land management condition targeted. It is helpful if all stakeholders of the project (those who will collect and use the information) can meet to determine the DSP project goal(s) and the target soil(s) and condition(s).

Determining DSP Project Goals

Project goals vary depending on the kind of project. Three kinds of projects are described below and examples are given for each.

DSP range study.—The goal of this kind of project is to evaluate the entire range of values for DSP properties and so provide soil component information regardless of land management or use. A single soil or group of closely related soils is selected. Land management conditions are not closely controlled (i.e., not specifically targeted in sampling) but should be well documented. This type of project requires the least amount of replication. Therefore, while results apply across the area of interest (soil group), the data typically is not sufficient for statistical comparisons between land management conditions.

> Example: The soil of interest occurs in an area used for rangeland, pastureland, and cropland. A DSP range study would sample a range of management systems across all three land uses, including those that are expected to have the smallest and highest DSP values.

> Example: A Midwestern U.S. State wanted to know typical values of DSPs across a region. For 2 years, all projects included sampling for DSPs as well as documentation of land use and management information for at least one pedon. The data provided a general idea of relative conditions across the region. There were no pairs or replications that could be used to make statistical comparisons because this was not the purpose of the project.

DSP baseline or reference study.—The goal of this kind of project is to establish baseline or reference DSP levels for a limited number of reference or land management conditions. The baselines can be used to interpret onsite assessments of soil health as a starting point for modeling or monitoring projects. Results apply across an area (a soil or group of soils) and the land management conditions of interest. Extrapolation beyond these conditions requires expert knowledge and depends on the extent and representativeness of the selected land management conditions. This type of project requires an intermediate level of replication across target soils and land management conditions.

> Example: Kirkland soil has particularly high soil function in a grazed native prairie with occasional fire (this is the reference condition of its ecological site). A reference DSP study would target this condition, and future evaluations and assessments could be compared to the baseline, or reference, levels.

DSP soil change study.—The goal of this kind of project is to assess soil change using the technique of space-for-time substitution. Instead of evaluating the effects of a management system in one location over an extended period of time, this technique compares two different locations that have had different management systems over the same period of time. It assumes that soil properties at the two locations were the same before the management system was applied. Typically, this type of study also serves as a baseline or reference study for a soil or soil group. In addition, soil change studies require the careful selection of land use and management conditions that represent a reference state and an alternative state. Robust multi-scale replication is required to make statistical conclusions about the soil change caused by land management. Pickett (1989) gives the theoretical background of space-for-time substitution, and Tugel et al. (2008) discuss the implementation of this technique in soil survey.

> Example: A group of soil scientists in Michigan wanted to investigate dynamic soil properties under two types of wetland restoration. They determined that they needed to conduct a DSP soil change study that included a baseline or reference state (in this case an undisturbed reference wetland) and alternative land use conditions with a multi-scale sampling scheme to capture variability within individual wetlands and across the project area.

Determining the Target Soils and Conditions

Studies can be designed to target soils, ecological sites, or land management conditions.

Soils or ecological sites.—Targeting a specific soil(s) or ecological site(s) will determine the extent of the DSP project, where samples and observations might be collected, and where the results should be applied. Approaches for targeting soils include single soil unit, soil system, and ecological site.

Single soil unit.—The smallest unit of the study interest is a map unit component represented by a soil series. Benchmark soils that are representative of other soils in the area and/or represent important resource concerns and ecological processes are selected.

> Example: In an area of Michigan, the organic wetland soil Houghton is the most common soil in restored wetlands. The Adrian soil is very similar taxonomically and occurs in the same landscape positions. Both soils were therefore considered target soils for sampling and comparisons.

Soil system.—A study of a soil system segments the landscape and evaluates appropriate hierarchies in a soil system or catena. Soil components that represent similar portions of the landscape and/or respond similarly to land use and management conditions can be combined for sampling purposes.

> Example: In Renville County, Minnesota, the soil landscape was segmented into three parts based on topography, hydrology, and the reflected taxonomic classes (fig. 9-2). One individual soil component was chosen to represent each of the three groups.

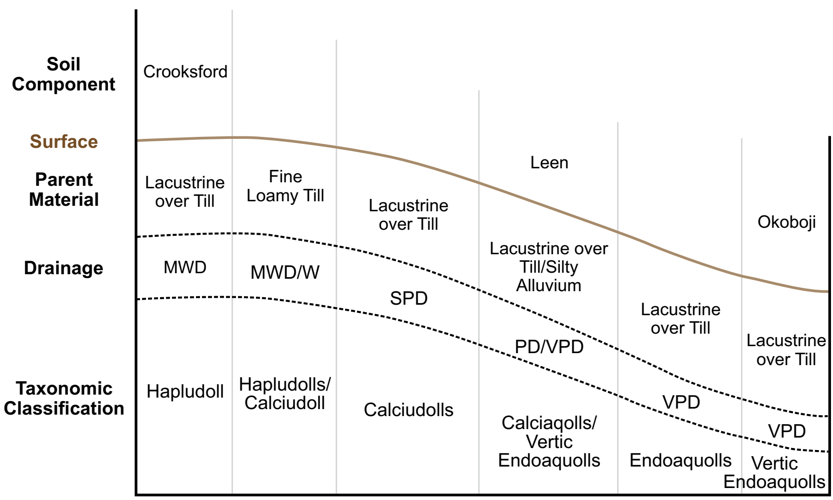
Ecological site.—The study of an ecological site groups soil components into units that are meaningful for ecological processes and land management.

Land management conditions (for reference, baseline, or comparison).—The land management conditions are selected according to the soil and type of project and can include general land cover classes (e.g., rangeland or cropland) or specific management systems (e.g., 3-year burn cycle with moderate grazing or no-till corn with cover crops). For each project, a similar level of variability within the specified land management conditions needs to be maintained. For example, comparing forested conditions within a reference state to a specific cropland management system may be more appropriate than comparing all forested conditions under a specific management system. When trying to document soil change, the chosen conceptual model should partition soil change into discrete frames of reference, conditions that can be put into separate categories (Starfield et al., 1993) and that can be sampled at separate physical locations (using the space-for-time technique). The *Soil Change Guide* (Tugel et al., 2008) recommends using common models of soil disturbance and erosion, such as STIR, RUSLE2, and SCI (Foster, 2005; Hubbs et al., 2002; USDA-NRCS, 2003, 2006). Wills et al. (2016) outlined a potential framework for grouping management systems by primary production groups and types and amount of disturbance.

> Example: A DSP planning team in Michigan determined that in order to meet their goals a baseline reference wetland needed to be sampled and documented in addition to two general types of wetland restoration and typical agricultural production.

> Example: In Dodge County, Nebraska, two agricultural management systems were chosen as the target conditions. The reference condition was the highest functioning agricultural land use.

Figure 9-2



A generalized cross-section of a soil landscape near Olivia, Minnesota. A DSP project was designed to capture the effect of land use change on the soil system. Crooksford components represented relatively well drained Hapludolls, Leen components represented Calciudolls and Calciaquolls on depression rims, and Okoboji components represented Endoaquolls in depressions and lake plains. (Drainage class abbreviations: MDW—moderately well drained, W—well drained, SPD—somewhat poorly drained, PD—poorly drained, and VPD—very poorly drained.)

Data Collection Plan

A written plan serves as both a tool for organizing work and a record of how the project was conducted for future data use.

Formalizing Project Objectives

Planning decisions are recorded. The project goals and the geographic and conditional constraints are clearly defined. This information includes identification of which soils and land management conditions will or will not be acceptable for sampling.

Gathering Existing Data

Relevant data in soil survey and laboratory databases can be located by querying for the target soil taxa or spatial joins or by other means. Relevant information may also be located in journal publications, extension publications, or graduate student work through nearby universities, colleges, or other groups.

Additional Data Collection

All DSP projects need to include a protocol for data collection across multiple scales. Sites (independent locations commonly sampled as plots) should capture the full range of soils and land management conditions of interest. Within each site, a minimum of three pedons should be located in a standard layout or in a random fashion. Methods, field forms, and equipment for field data collection are discussed in appendix 3 of the *Soil Change Guide* (Tugel et al., 2008). All information should be provided as general metadata about how the project was designed and executed.

Determining Sources, Types, and Amount of Variability

Expert knowledge of the system and existing data are used to identify sources of variability. Tools such as the Multi-Scale Sampling Requirement Evaluation Tool (Tugel et al., 2008) can be used, or estimates can be made for the number of sites (independent location) and pedons per site needed to meet project objectives.

Designing a Sampling Scheme

The best arrangement of pedons within sites can be determined using the information about expected variability. The sampling scheme should include multiple sites or locations across the spatial extent of the study. The design should not under- or over-represent landscapes (e.g., hummocks or depressions) or microfeatures (e.g., trails or tree-throw) within a site. Figure 9-3 shows a sampling scheme.

Locating Sites for Data Collection

Field sites should represent both the central concept and the typical range of properties for the target soil and land management conditions. Care is needed to avoid bias in location selection. GIS techniques, such as conditioned Latin hypercube sampling, or other statistical sampling techniques can be used. Alternate locations should be chosen in case a site cannot be accessed or must be rejected. Brungard and Johanson (2015) describe a rigorous plan for substitution.

Developing data collection and sampling plan.—The protocols and procedures for DSP project sampling need to be planned. The data elements and terminology used must be compatible with the soil system. The top image in figure 9-3 shows how sites can be distributed across a region. Figure 9-4 shows pedon distribution within a paired site in Dodge County, Nebraska. In this project, sites were located as pairs (with both target land management conditions present) to limit soil variability and improve condition comparisons.

Guidelines for accepting or rejecting a site for sampling.—For most soil survey applications, soils and conditions should be verified in the field to ensure that sampling will meet project objectives. Guidelines should outline the ranges of soils, features, and land management conditions that are acceptable for inclusion in the project.

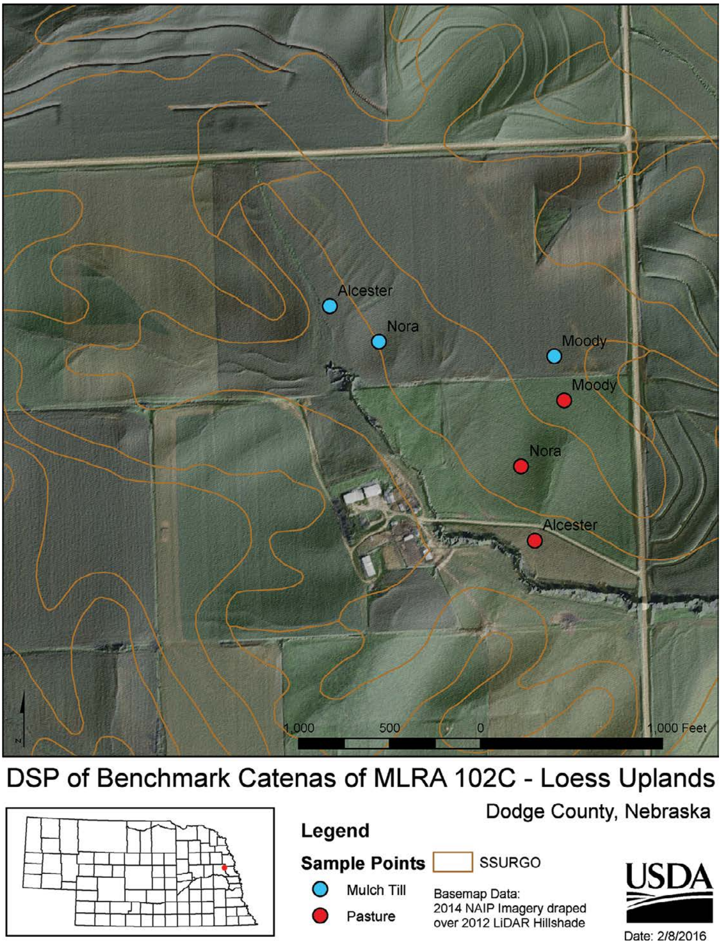
List of data elements for site information.—Management and vegetation data are typically collected at the site scale. All data elements to be measured or recorded at each site (location or plot) should be identified. They may include vegetative cover, residue, site index, or other metrics of vegetation or management. Common collection schemes for ecological site data in the project area can be used as a starting point. Table 9-1 is an example of elements that might be collected at each site, location, or plot.

Instructions for locating individual pedons and measurements.— A clear plan is needed to explain how pedons will be located within each site as well as where and how any associated surface properties will be measured. It may include a standard plot layout (fig. 9-5), randomly positioned pedons within a plot area, or transects (fig. 9-4) with pedons positioned at regular intervals along a catena contour. A plan for measuring infiltration, hydraulic conductivity, and surface features (such as residue, pattern class, and soil crust) before pedons are disturbed improves data integrity.

Figure 9-3

Documentation from the Georgia Longleaf Pine Dynamic Soil Property project (unpublished data). Care was taken to include both target land use conditions across the study area. Top: Distribution of plots across the major land resource area (MLRA) 133A. Plots were labeled to designate them as being on the A (Atlantic) or G (Gulf) side of the region and as P (pasture) or L (longleaf pine). Bottom left: A longleaf pine plot. Bottom right: A pasture plot with a transect tape (for vegetative cover measures). County names and boundaries are shown on the map. (Photo courtesy of Dan Wallace)

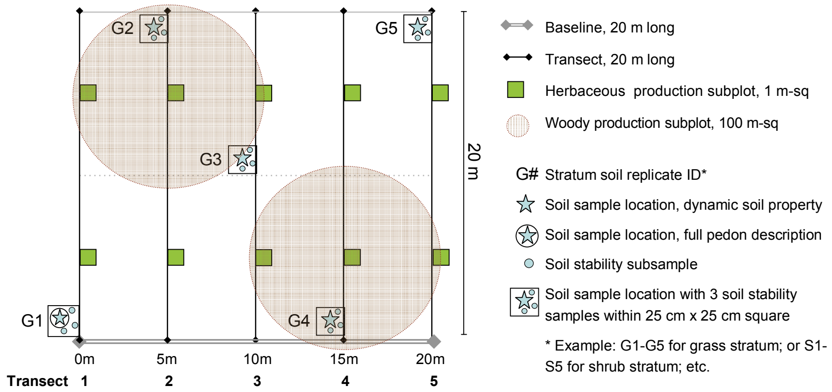
Figure 9-4



Example of pedon placement for a paired site in Dodge County, Nebraska. Each site has both target land management conditions (pasture and corn-soybeans with mulch tillage). The soil system was captured with three target soils. The central pedon location is represented on the map and labeled with the soil name. Two additional satellite pedons located along the contour are not shown on the map.

Instructions for pedon sampling and description.—Descriptions of pedons to a predetermined depth should follow standard procedures (see page 8-2 of Schoeneberger et al., 2012). It is suggested that one pedon per site be observed, one pedon per condition be sampled to a depth necessary for soil series confirmation, and detailed high-quality information, such as bulk density and water retention analysis, be collected for those pedons (table 9-2).

Figure 9-5



Instructions: The baseline should be positioned obliquely to the slope and 5 transects should be positioned at approximately 90° from the baseline parallel to one another. The individual placing the flags will fill out the "Sample Locations and ID" portion of the "Plot Master" field form while identifying and flagging the soil sample locations. The flags will be pre-labeled with the Stratum-soil replicate ID (e.g., G1-G5). At each soil sample location, stability samples, penetrometer readings, bulk density samples, and soil samples for laboratory analysis will be collected. Line-point intercept and GAP will be completed along each transect. Place herbaceous subplots at meter marks 5 and 15 on each transect. Woody subplots are centered at transect 2, meter mark 15 and transect 4, meter mark 5. Complete 1 Pedoderm and Pattern Classes form for each plot (Tugel et al., 2008).

Example of detailed plot sampling instructions for a rangeland DSP project in Utah. Because the project involved both soil scientists and range scientists, a highly detailed plan was developed for sampling. From the Soil Change Guide *(Tugel et al., 2008).*

Table 9-1

DSP Project Data Elements Collected at Site (Across Plot) Scales

Type of data	Property/measurement
Management information	Crop rotation
	Tillage system
	General description
	Tillage operations (frequency and timing)
	Applications and other operations and treatments
	Grazing management
	Forestry management

Type of data	Property/measurement
Vegetation information (as appropriate)	Plant biomass or production
	Composition
	Understory
	Overstory
	Line-point intercept
	Canopy and basal gap
	Site index
Forest floor (when present in any part of study)	Woody debris
	Visual disturbance classes*
	Soil surface displacement, compaction, litter thickness, crust cover, etc.
Surface properties	Residue cover/bare soil
	Pedoderm and pattern class+

* Page-Dumroese et al., 2012
\+ Burkett et al., 2011

Table 9-2

DSP Project Data Elements Collected at Pedons; Multiple Locations per Site/Plot

Type of data	Property/measurement
Surface properties	Aggregate or soil stability
	Infiltration
	Single ring
	Double ring
	Crust description (when present)
	Pedoderm and pattern class
	Relevant microtopography
	Soil surface temperature
	Cover/bare soil
Pedon properties	Pedon description
	Horizon depths, colors, textures, fragment estimates

Table 9-2.—continued

Type of data	Property/measurement
Pedon properties	Agronomic feature (furrow, wheel-track, etc. at pedon location)
	Soil horizon/depth increment
	Temperature
	Cover/bare soil
	Saturated hydraulic conductivity

Instructions for sample collection.—Collecting a sample from a predetermined depth (e.g., 0–5 cm) near the surface helps in making comparisons between conditions. The kind of near surface horizon of the sample should be noted (see chapter 3). This sample can be treated as a subsample of the first horizon or described as a separate horizon. All other samples should be collected by genetic horizon to capture the most variability within the profile and allow comparisons between horizons. Because many DSPs are sensitive to disturbance, walking or using heavy equipment on sampling areas should be avoided. A plan for labeling samples is needed to keep track of soil, condition, site, and pedon replication as well as information on horizons and layers.

Instructions for sample handling.—Many of the properties measured in DSP studies are the same as those measured in standard soil survey procedures. The emphasis is on targeting, tracking, and replicating certain conditions. However, some measures are of particular interest for DSP sampling, such as bulk density, aggregate stability, and soil biology measures (e.g., enzyme activity). The samples should be handled carefully and not exposed to crushing or warming. Samples should be air dried as soon as possible if they are to be shipped and/or stored for more than 24 hours.

Desired minimal dataset for laboratory samples.—The dataset should have information on standard inherent properties to allow for correlation and comparisons between soils and sites. It may include standard pedon description information (such as horizon thickness, texture, and coarse fragments) and laboratory data (such as particle-size determination). At minimum, the DSP dataset should include carbon (organic and inorganic), pH, EC, bulk density, aggregate stability, biological enzymes (β-glucosidase is recommended), particulate organic matter, and nutrients (N, P, K, etc., as appropriate). Table 9-3 provides a potential list of properties to measure. The Kellogg Soil Survey Laboratory currently analyzes standard interpretive and dynamic properties.

Table 9-3

Measurements of Dynamic Soil Properties on Individual Samples

Type	Property/measurement
Standard interpretive	Standard laboratory characterization
	Particle-size determination
	Other properties *in lieu* of particle size
	Minerology (clay or other as appropriate)
	CEC
Standard dynamic	Organic carbon
	Derived from total and inorganic carbon
	Inorganic carbon
	Derived from calcium carbonate equivalent
	pH
	EC
	Bulk density
	Aggregate stability
	Water stable aggregates
	Total N
	P (Mehlich or other as appropriate)
	Water retention
	Extractable bases
	Extractable acidity
	ECEC
	Permanganate extractable carbon (POX-C or Active C)
	Soil enzymes
	β-glucosidase
	Particulate organic matter (POM)
Supplemental as needed and available	SAR
	Plant available P
	Dry sieve aggregates
	Potentially mineralizable N

Table 9-3.—continued	
Type	**Property/measurement**
Field lab	pH
	Active C (kit for permanganate extractable C)
	Aggregate stability
	Advanced soil structure and pore analysis
	CO_2 burst and respiration tests

Analyzing Dynamic Soil Property Data

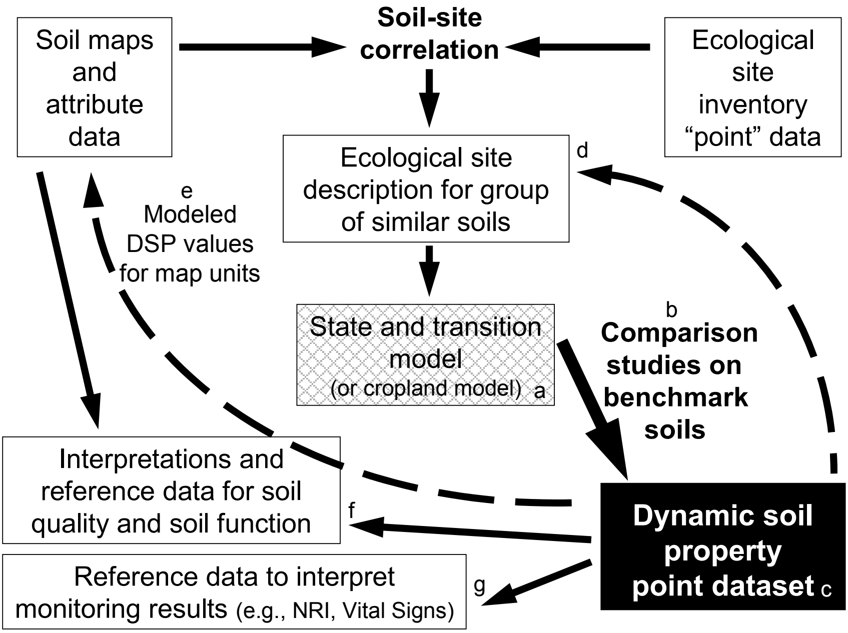
DSP data can be used for many purposes, some directly related to soil survey and many others that are indirectly related (fig. 9-6). The first and most long-lasting outcome of a DSP project is the collection and documentation of soil and vegetation data under various land use and management scenarios. This is an immediate product that can serve as input for many other products, such as conservation effects modeling and general geospatial analysis.

Initial steps for DSP data analysis are the same as those for any aggregation of soil survey data. The data compilation is complicated by replication across sites and pedons. Good recordkeeping and labeling throughout the process help ensure reliable results. To allow for improvement over time, all data aggregation should be documented through written records, program scripts, and public databases. The following outline describes several important steps and considerations in analyzing DSP data.

DSP Data Handling

1. **Maintain the project's data collection plan.** The data collection plan serves as the metadata for the project and will explain to future data users how and why the data was collected.
2. **Enter and check data for errors.** Enter data into required programs and databases and examine it for errors. This data includes information about the sites, pedons, samples collected, and land management systems. Some information (such as infiltration rate) may be collected in the field and recorded later in a database or other file structure.

Figure 9-6



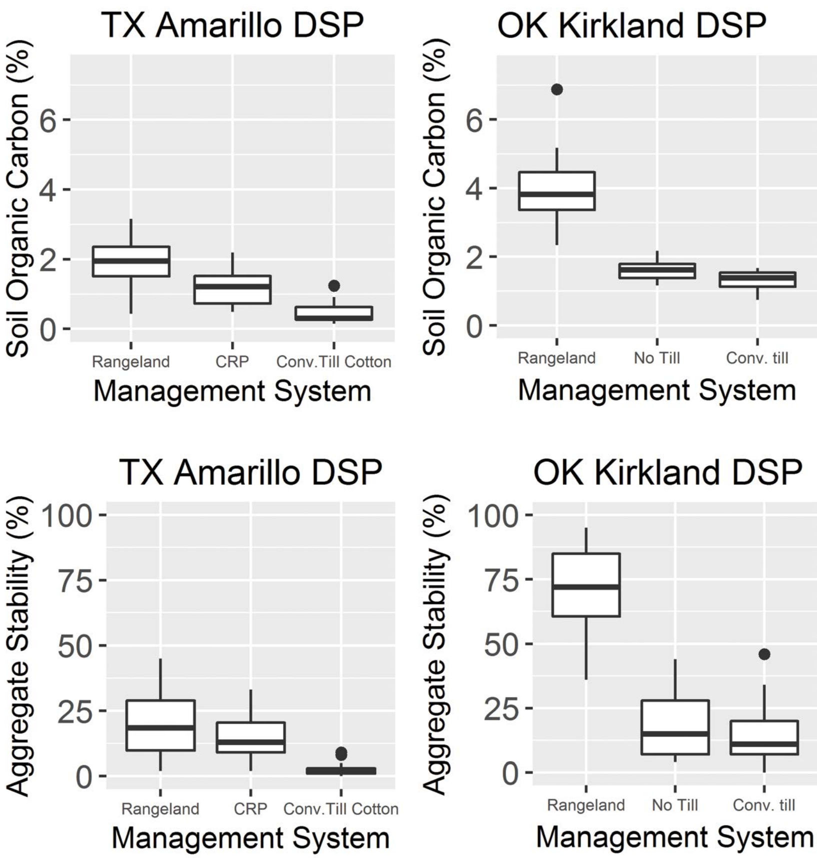
Dynamic soil property data in relation to ecological sites, soil interpretations, and monitoring data. A simple conceptual model (a) is used to design comparison studies (b). Dynamic soil property data derived from these studies are used to populate a point dataset (c). The point data are then available to include in ecological site descriptions (d), model dynamic soil property values for similar soils (e), develop interpretations (f), and interpret monitoring data collected through programs (g), such as the Natural Resources Inventory (NRI), Vital Signs, and Forest Inventory and Analysis (FIA). From Tugel et al., 2008.

3. **Compile or link data across common scales.** Link and label DSP data, as appropriate, to include site and observation information (e.g., vegetation and individual pedons from the same site are labeled with the same plot ID). A robust database should allow for the association of data elements across conditions and locations.
4. **Generalize horizons and other units of measure.** Data collected by samples that are individually labeled, such as by genetic horizon, must be grouped into common units so that properties can be analyzed and compared. Add other data elements (such as comparable layer; Tugel et al., 2008) that

group all possible horizons in the project. Keep scripts and rules as part of the project metadata and documentation.

5. **Aggregate individual observations and measurements.** From the smallest individual data element (sample values) to the broadest level of interest (soil and land use or management system), select meaningful comparisons between conditions. Aggregate horizons, pedons, and sites to make comparisons.
    a. Create separate data elements for surface samples (0–5 cm) and comparable layers, such as all A horizons or all B horizons or other combinations outlined in the *Soil Change Guide* (Tugel et al., 2008).
    b. Use weighted averages by depth to combine horizons into pedon values.
    c. Compute statistical measures for plots or sites.
    d. Compute statistical measures for land use or management.
6. **Analyze data.**
    a. Perform data evaluation and graphical comparisons. Preliminary data is evaluated to gauge general trends, identify errors, and locate any outliers. Graphs should include box plots by comparable layers, pedons, and sites and depth functions within pedons. Figure 9-7 shows a summary of two surface layer DSPs for two separate DSP projects. Data visualization can be used to explore, examine, and share general conclusions about the project.
    b. Calculate descriptive statistics across soil groups. Initial summary statistics include central tendencies (mean, median, and mode) as well as measure of dispersion and variability (range, standard deviation, etc.).
    c. Calculate descriptive statistics for individual land management conditions (as appropriate). Calculate measures of central tendencies, dispersion, and variability. Use site averages or a mixed model to accurately reflect any autocorrelation between observations taken at the same site.
    d. Conduct statistical comparison and ascertain meaningful differences. Evaluate statistical differences between land management conditions.
        i. Use T and F tests for differences. Mixed models optimize use of fixed (condition) and random (plot replication) factors.

Figure 9-7



Dynamic soil properties of 0–2 cm samples for two DSP projects (Amarillo and Kirkland soils) for: a) soil organic carbon (%) measured as total carbon and b) water stable aggregates (%). Box plots represent the 25th and 75th percentiles. Note that rangeland was used as a reference condition for both projects but that different alternate land management systems were used for comparison. The soils also have different reference levels of these two DSPs.

ii. Examine literature to determine if described differences are meaningful to soil function.
iii. Evaluate sampling sufficiency (e.g., were enough samples collected to detect a difference if one exists?). If properties are more variable than originally anticipated, the sampling design

may not have the power to detect anything other than a very large difference. Additional sites can be chosen and samples collected so that meaningful statistical comparisons can be made to detect smaller (but important) differences in DSP values.

7. **Make inferences about soil variability, land management conditions, and soil change.** A final report should summarize the project goals, the target soils and land management conditions, the data collection process, and the methods of data aggregation and analysis. Final conclusions should include the most specific level of evaluation and the expected area of inference (i.e., other areas where the results might apply). This report serves to document the process and support any conclusions.
8. **Populate soil survey databases (such as information for soil map unit components) as appropriate.** Depending on the nature of the project, report results for the entire extent of the soil (or soil group) or report results as being limited to certain conditions.

Care should be taken when incorporating DSP project data into standard data aggregation. Consider the distribution and representativeness of data when populating general component information, such as representative values (RV). If differing management conditions have statistically different DSPs, compare the distribution of the conditions assessed to the number of pedons available for aggregating. You may need to aggregate by land management condition and then weight the conditions by spatial prevalence to arrive at an overall value.

Summary of DSPs in Soil Survey

Dynamic soil properties enhance soil survey by providing information about soil properties that change with land use and management. Information about DSPs improves the ability to document, explain, and predict the effects of land use and management on soil and ecosystem function. DSP data can be collected as general information or as projects designed to detect statistical differences between management and land use types. In both approaches, DSPs are collected in a way that documents both soil properties and classifications and land use and management information. Careful planning, sampling, and analysis ensure that DSP data enhances soil survey projects and allows for additional use of soil information.

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CHAPTER 10

Subaqueous Soil Survey

By Mark Stolt, University of Rhode Island, and James Turenne and Maggie Payne, USDA-NRCS.

Introduction

Subaqueous soils differ from subaerial, or terrestrial, soils by having perennial water on the soil surface. These soils occur in shallow freshwater and marine environments, such as ponds, lakes, and the subtidal areas of estuaries and tidal embayments. The Soil Survey Staff (2014) defines "shallow" as approximately 2.5 m. At depths greater than 2.5 m, sunlight is typically attenuated and submerged aquatic vegetation (SAV) is typically absent. In especially clear waters, however, this depth may be much greater. Thus, for interpretive purposes, mapping is typically done to depths of 5 meters of water. Areas with extreme tidal ranges are also included as subaqueous soils even though they may be exposed for an hour or two during a neap tide or similar event. Subaqueous soils occur on a range of subtidal and limnic landforms, such as flood-tidal deltas, washover fans, and lake beds (Schoeneberger and Wysocki, 2012; USDA-NRCS, 2016). These soils are currently classified in the Histosol and Entisol orders of Soil Taxonomy (Soil Survey Staff, 2014).

Occurrence

Subaqueous soils occur worldwide, except in the driest inland areas where water does not pond permanently to form lakes or ponds. In coastal areas, these may be the most extensive soils on the landscape. For example, Rhode Island has approximately 700,000 acres of subaerial soils. If the area of subaqueous environments having water depths of less than 5 m are included, the total area of soils would almost double.

Importance

The world's population centers are in coastal areas. In the United States, coastal watershed counties make up less than 10 percent of the land area, but more than 50 percent of the population lives in these counties. If the cities and towns within a short distance of the Great Lakes were included, that number would be significantly larger. Coastal and inland waters are used for transportation, recreation, farming, and other livelihoods. From an ecological perspective, shallow and inland waters are the nursery grounds for most of the animals that inhabit these ecosystems. The subaqueous soils in these shallow habitats provide the foundation and structure of the ecosystem. The many anthropogenic activities in the shallow water habitats disrupt, disturb, and may even destroy these habitats. Therefore, understanding the distribution and characteristics of the subaqueous soils is critical to properly managing and using these habitats so that these ecosystems properly function and continue to be healthy and vibrant. The use and management of subaqueous soils in shallow water ecosystems may include dredging, dredge placement, restoration of submerged aquatic vegetation, identification of areas for shellfish aquaculture, restoration of wild stocks of shellfish, and identification of areas for docks and moorings (e.g., Stolt and Rabenhorst, 2011; Erich et al., 2010).

Sampling, Description, Characterization, and Classification

Chapters 2 and 3 provide standards for describing soil profiles and their site characteristics in the subaerial settings common to soil survey. The subaqueous soil environment presents unique challenges for observing soil profiles, collecting samples, and describing soil properties. This section provides information specific to subaqueous soils. The *Field Book for Describing and Sampling Soils* has a section that provides important information specific to mapping, describing, and sampling subaqueous soils (McVey et al., 2012).

Sampling

Subaqueous soils can be sampled by several traditional soil approaches, but marine science approaches are best. For cursory descriptions and sampling, a standard bucket auger can be used. In order to sample from the exact location with depth, some soil mappers use a piece of PVC pipe with an inside diameter a little larger than the teeth on the bucket auger. The auger is placed into the pipe, and the sample is collected in the typical fashion. While the bucket is being removed, the PVC pipe is pushed deeper into the soil. The sample is retrieved and placed in a tray (typically a meter-long piece of vinyl gutter). The auger bucket is pushed down the pipe again, the spoil from pushing the PVC pipe down is removed, and then the next depth is sampled. This procedure is effective for sampling the upper 75 cm of the soil. Below this depth, however, collecting samples with a bucket auger becomes very difficult.

In shallow water where soils are non-fluid, sampling with a bucket auger can be done while wading. A small light raft (typically made from floating dock material of Styrofoam) works well in holding the sample tray. A small anchor (e.g., a brick with holes) is used to keep the raft in place. In deeper water, samples can be collected from the side of a boat. A boat with a deck at the bow can be used, but a pontoon boat with a 60 x 60 cm sampling port cut into the deck between the two pontoons (i.e., a moon-pool) is preferred (fig. 10-1). The boat is anchored at two points, and the bow faces into the wind or the direction of oncoming waves to keep the boat in the place while sampling. Sampling should be avoided if there is significant wind or waves. In freshwater systems in northern climates, sampling can be done through ice. A standard ice auger is used to cut a hole in the ice, and the soil is sampled through the hole.

For organic soil materials or fluid mineral materials, a Macaulay peat sampler is very effective. Most Macaulay samplers have sampling chambers 50 cm long. Machine shops can construct auger chambers to longer lengths (such as 1 m), which work well for subaqueous soil sampling. These samplers can be used easily through the moon-pool, off the side of the boat, or through a hole in ice. Because water depths vary, extensions on the bucket auger or peat sampler should be easy to add on or remove.

For detailed sampling and description of non-fluid materials, a vibracore sampler is ideal. Vibracore samplers consist of a concrete mixer motor, a cable that delivers the vibration from the motor to the sampling tube, and a vibration head that clamps onto the irrigation pipe (core barrel) to deliver the vibration to the core barrel that collects the sample (fig. 10-2). The vibration loosens (or liquefies) the soil material around the core barrel so that the core can be easily pushed into the soil with a minimal amount of pressure from the top of the pipe. This sampling approach is typically done from a pontoon boat with a moon-pool. If the body of water is too small for a pontoon boat, or gas-powered

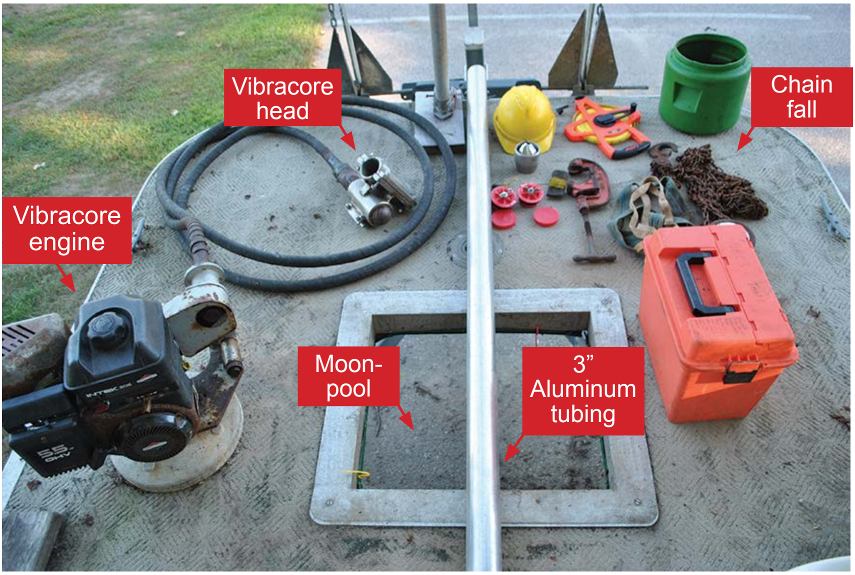
Figure 10-1

A pontoon boat used for subaqueous soil sampling. The sampling is conducted through the moon-pool. A sealed core is strapped to the end of the chain fall. The chain fall is attached to the tripod, which is centered over the moon-pool.

boats cannot be used, a small barge with a moon-pool in the middle can be used. In this case, the concrete mixer motor is in the small boat used to pull the barge and the soil is collected and retrieved through the moon-pool in the barge. There are "backpack" types of vibracores that can be used off barges or through the ice. In some cases, these types of corers are not powerful enough to push the tubes through dense soil materials.

Core barrels used for vibracoring are typically 10 cm in diameter (fig. 10-3) and should be long enough to accommodate both the soil sample and the overlying water. Once the barrel is pushed into the soil to the desired depth, a lead weight (sinker) attached to a string is

Figure 10-2

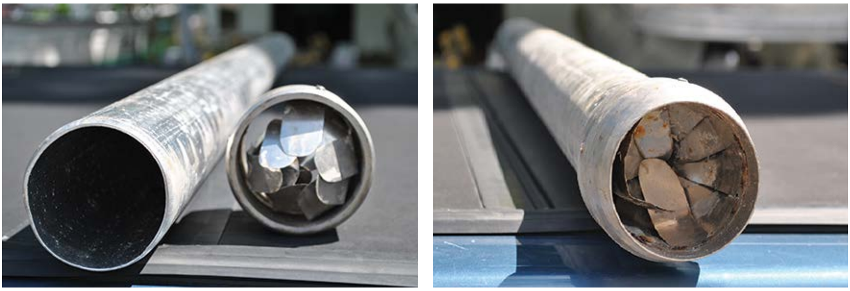


Equipment for vibracore sampling. A vibracore sampler consists of an engine, cable, head, and core barrel. The engines are typically gasoline driven (sold as a device to keep concrete mixed so it does not set). The cable carries the vibrations to the head, which is attached to the core barrel with four bolts.

dropped into the core barrel to measure the distance from the top of the core barrel to the soil surface in the tube. The same thing is done on the outside of the core. These measurements are made to determine the amount of collapse (settlement) that has occurred to the soil during coring (McVey et al., 2012). Significant collapse should be noted when recording horizon depths and reporting soil bulk density.

To retrieve the soil, the core is first slowly filled with water. A cap (test plug) is placed on the top that, when tightened, seals the top of the core. This creates a suction and, for most materials, keeps all of the soil material in the core barrel when it is removed. In some soil materials, particularly those that are coarse textured with many rock fragments, some of the soil material may fall out of the bottom of the core barrel when it is retrieved. In these cases, a core catcher can be added to the base of the core before it is vibracored into the soil (fig. 10-3). Once the core is sealed, it is attached with a heavy strap to a winch or chain fall and pulled out of the soil. Using a chain fall attached to a tripod mounted

Figure 10-3



A core barrel and core catcher. Left image—Core barrels used for vibracoring are typically 10 cm in diameter. The view of the sand catcher is from the perspective of the inside of the barrel. Right image—For sandy or loose materials, a core catcher may be attached to the bottom of the core barrel.

over the moon-pool is the safest way to remove the core (fig. 10-1). For sampling off a barge or through the ice, an aluminum ladder is commonly used instead of the tripod because of its lighter weight.

Once the core is pulled from the soil and sealed at the bottom (to prevent loss of the sample), a small hole is created in the irrigation pipe just above the top of the soil in the core barrel to allow the water on top of the core to drain slowly (see above information on measuring the depth from the top of the core barrel to the top of the soil). After the water is drained, the tube is cut just above the soil surface with a tube cutter and the cap is screwed back in place to preserve the core. The bottom is sealed with a cap first to prevent loss of suction. The core barrel is dried and clearly labeled with a pedon number and the correct orientation. The core can be opened on the boat, or it can be stored in a rack and later described and sampled on land or in a lab. Vibracores in the lab should be maintained at 4 ^{0}C to minimize drying and oxidation of sulfides prior to sampling and analysis.

Core barrels are best opened by laying the core down on a table or lab bench and cutting lengthwise on opposite sides with electric metal shears (fig. 10-4, top image). A circular saw works but creates safety issues and produces aluminum shavings, which need to be collected. A piano wire or steel guitar string is slid between the cuts in the aluminum tube to split the core in two. The two sides are lifted apart. One side is described and sampled, and the other is archived if needed (fig. 10-4, bottom image).

Figure 10-4

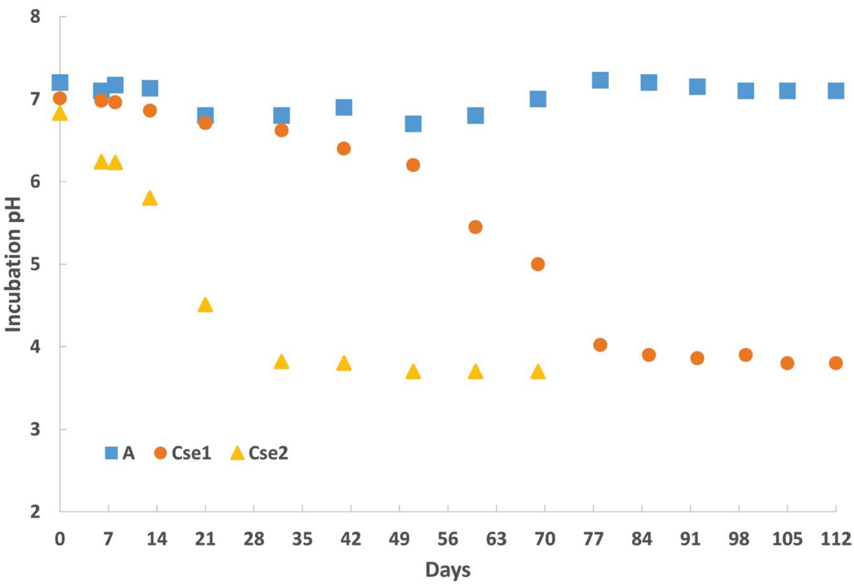
A core from subaqueous sampling. Top image—Cutting open the core with electric shears. Bottom image—A split core exposing the soil. One side is typically sampled, and the other may be stored and archived.

Description

In general, subaqueous soils are described the same way as subaerial soils (Schoeneberger et al., 2012) but using the setting terminology, sampling method, and various chemical and morphological properties of subaqueous soils described by McVey et al. (2012). It is worth reiterating that caution is needed when estuarine soils are sampled and described since these soils typically have significant amounts of sulfides. Once soil materials containing sulfides are removed from their natural state (underwater), the sulfides begin to oxidize (even when stored in a sealed core barrel at 4 ^{0}C). Mono-sulfides are more reactive to oxidation than di-sulfides, such as pyrite. The oxidation of sulfides may cause a change in soil color and a rapid decrease in pH as the sulfides are converted to sulfuric acid (in some cases pH decreases from more than 7 to less than

3; see fig. 10-5) (Fanning et al., 2010; Rabenhorst and Stolt, 2012). If the materials have a very low pH, the aluminum pipe housing the soil core may start to corrode and create Al salts. If soil color, pH, salinity, and particle-size distribution are important to the soil characterization, the soils should be sampled and described as soon as possible or samples should be frozen immediately after sampling to minimize the amount of sulfide oxidation.

Figure 10-5



Incubation pH for three horizons (A, Cse1, and Cse2) from a Fluventic Sulfiwassent, collected from the Thimbles Island estuary in Connecticut. Samples that have a pH of 4 or less after 16 or more weeks of moist incubation and that have a drop in pH of at least 0.5 unit meet the requirements for sulfidic materials. Both the Cse1 and Cse2 horizons meet these requirements. The Cse2 horizon attained the critical pH in less than 4 weeks while the Cse1 horizon took almost 12 weeks to reach a pH of 4.

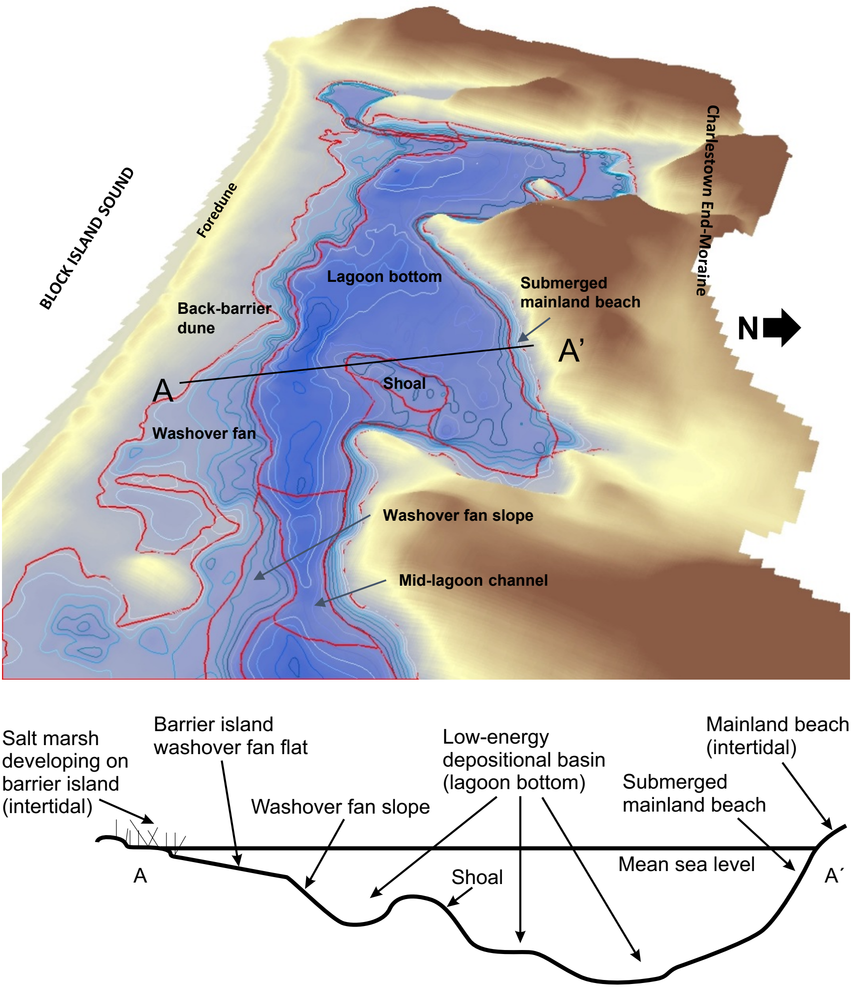
Important Properties for Classification and Interpretation

Soil properties important for classification and interpretations of subaqueous soils include type of organic soil materials, content of soil organic carbon, electrical conductivity (EC), fluidity, incubation pH, content of pore-water sulfides, particle-size distribution, mineralogy, and soil color. The presence of odors (such as sulfur or petroleum), the presence of shell fragments or former vegetation, and the nature of the depositional environment are also important. Subaqueous soils that are dominated by organic soil materials or are fluid cannot support dock pilings and typically require special moorings (Surabian, 2007). Electrical conductivity is used to discern between freshwater and estuarine soils and to identify soils that may have halinity issues when dredged and placed on the soil surface. Incubation pH is a measure of the potential acidity of the soil materials. Subaqueous soils dominated by mono- and di-sulfides may have dramatic drops in pH when dredged and placed on the land surface. In some cases, pH values decrease to less than 4 and acid sulfate soils are created (Clark and McConchie, 2004; Fanning et al., 2010). High sulfide contents, especially in the pore waters, can be toxic to submerged aquatic vegetation and may indicate a highly anoxic environment uninhabitable for many benthic organisms. Subaqueous soils typically have low chroma (< 2) and a neutral (N), yellow (5Y), or blue-green (BG) hue. Brighter chromas (> 2) or redder hues commonly indicate aerobic inputs (from ground water or the water column) or relict subaerial soils that are now submerged (see lower part of core profile in fig. 10-4, bottom image).

Soil-Landscape Relationships

Like subaerial soils, subaqueous soils form as a result of various additions, losses, transfers, and transformations occurring within the soil (Simonson, 1959). The dominant processes that form a particular kind of soil depend on where the soil occurs on the subaqueous landscape. Figures 10-6 and 10-7 provide examples of coastal lagoons, which are very common in estuarine systems along the U.S. Eastern Seaboard. Large areas of the basins (bottoms) of coastal lagoons are dominated by fine textured (silt loam and silty clay loam) soils that are rich in sulfides, are very fluid, and have a high content of soil organic carbon to a depth of 2 m or more. Because the lagoon bottom is in a low-energy position, only fine particles (very fine sand or finer) and organic matter are deposited. Little oxygen is available for microbial respiration, and redox potentials are very low. As a result, the transformation of sulfate to sulfides dominates the soil processes. With continued additions of organic matter and little decomposition at the low redox potential, levels of soil organic carbon remain high. Because the silt- and clay-rich parent materials have such fine particles sizes, which are not readily compacted in the permanently inundated low-energy environment, very fluid soils form.

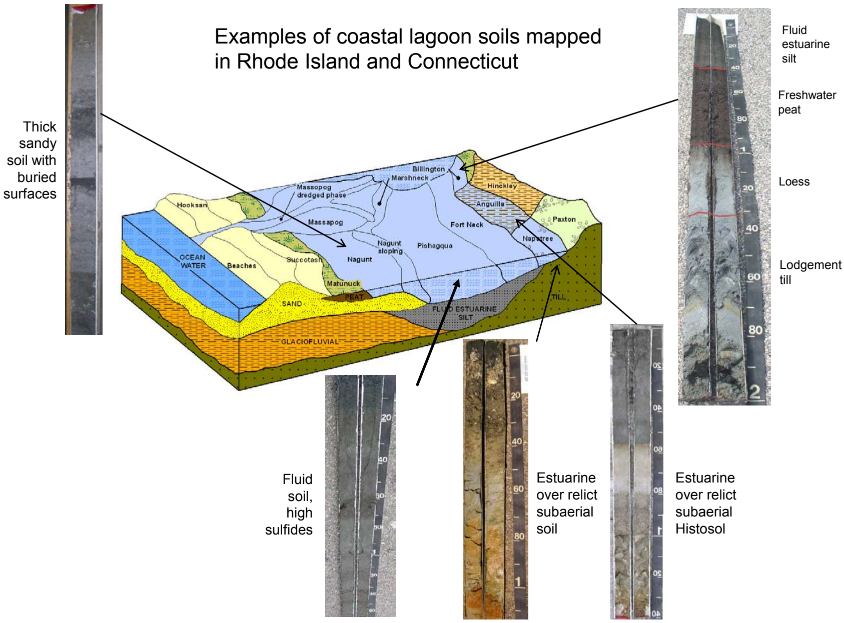
Figure 10-6



Examples of subaqueous landscape units across a coastal lagoon.

Higher on the coastal lagoon subaqueous landscape, typically between the deeper lagoon bottom and the shallower washover fan, water currents have more energy than those in the lagoon bottom where the finest particles and organic matter settle out. During storm events, there is even greater energy due to an increase in waves, fetch, and nearby overwash events and coarser (sand-sized) particles are deposited. Where benthic organisms are continuously mixing the upper part of the soil, textures are

Figure 10-7



Soil-landscape relationships across a coastal lagoon in Rhode Island and Connecticut.

loamy and fluidity is low. In this part of the landscape, subaqueous soils develop A horizons and sulfidic materials are not typically found in the upper horizons because of the mixing and elevation (shallowest water depth).

Adjacent to the barrier island that separates the lagoon from the open ocean, washover fans are the dominant landscape unit. The frequency of overwash events that reach the washover fan increase with decreasing distance to the barrier island, and the soils typically do not have A horizons.

Freshwater systems such as ponds, reservoirs, and lakes are typically low energy. These environments typically do not have the highly depositional and erosional landscape units (such as deltas, washover fans, or current-formed channels) found in estuarine settings. Thus, the landscape patterns in the freshwater systems are much simpler than those in the estuarine systems. For example, Payne (2007) identified a total of 21 different landscape units in her study of three shallow estuarine embayments in Rhode Island. She noted that differences in geology, geomorphology, geography, wind, and tidal patterns accounted for much of the variation in landscape units. In contrast, Bakken (2012) studied six natural and impounded freshwater systems and found only four landscape units (cove, shoal, lakeshore, and lakebed).

There have been two studies of freshwater subaqueous soils (Erich et al., 2010; Bakken, 2012), and both found that soil characteristics in freshwater systems were more influenced by the geologic and anthropogenic history than by the landscape. The subaqueous soils in reservoirs were very similar to those prior to impoundment and flooding. The natural lakes were primarily kettle holes that slowly filled with rising ground water. In most cases, organic soil materials accumulated in the kettle holes when they were wetlands (subaerial soils) with little mineral inputs after permanent inundation and ponding. Thus, these soils typically were Histosols. In areas where there was significant anthropogenic input of nutrients, invasive species such as milfoil (*Myriophyllum* sp.) and fanwort (*Cabomba caroliniana*) proliferated and thick deposits of plant-derived organic materials accumulated, forming present-day subaqueous Histosols.

Survey Methods and Procedures

Special methods and procedures are used to develop base maps for conducting subaqueous soil surveys. Additional remote sensing tools and techniques can also be useful for preparing subaqueous soil survey maps.

Bathymetry

Developing soil-landscape relationship models is critical to the mapping of subaqueous soils (Bradley and Stolt, 2003; Osher and Flanagan, 2007). The first step is obtaining bathymetric data and creating a bathymetric map of the subaqueous landscape (Bradley and Stolt, 2002). The bathymetric map serves the same purpose as the topographic map. Aerial photos, if the water clarity was good on the day the photos were taken, can be helpful in the identification on the map of exact boundaries of landscape units, such as washover fans, shoals, and submerged beaches.

In some areas, accurate bathymetric maps are already available; in other areas, they may need to be created. Bathymetric maps are created by systematically collecting water depth data while recording x and y coordinates. Water depth is typically determined using a fathometer mounted to the hull of a boat. The boat is slowly driven across the water body for a series of transects. Transects are spaced 20 to 30 m apart, and data are collected every 5 to 10 seconds, depending upon the speed of the boat. Each time a water depth is recorded, the x and y coordinates are also recorded with a global positioning system (GPS). A fairly simple fishfinder with GPS capabilities can collect the x and y data and the z (water depth) data at the same time. Caution is needed in areas with dense submerged aquatic vegetation (SAV) since the fathometer may read the top of the SAV as the soil surface. In these cases, manual readings of the water depth should be occasionally collected and checked against the fathometer values. Several transects are also completed parallel to the shoreline to augment the other transect data. In freshwater systems, the water depths can be corrected to the mean water level of the water body. In tidal systems, tidal fluctuations need to be recorded at the same time as the x, y, and z data to correct the water depth data. Any water-level recording device that has time-stamped data can serve this purpose. In areas where tidal fluctuations are complicated, as many as three water-level recording devices may need to be used at one time. In most cases, however, a single-water level measurement device can be used and moved to new locations as the bathymetric data are collected. Because of recent advances in Light Detection and Ranging (LiDAR) for underwater applications, accurate bathymetric maps may eventually be available for most coastal environments.

The bathymetric data are imported into a GIS program to create the contour maps. They are typically kriged, and a stop line is set at the tidal datum chosen as the elevation where the water meets the land. All bathymetric data collected in tidal systems are normalized to NAVD-88 or new vertical datum if available. McVey et al. (2012) discussed the use of various datums for a bathymetric contour map. To normalize the data, the bottom depth (elevation) of each tide gauge must be determined using traditional land survey techniques from an order 1 benchmark. Changes in the shallow subaqueous landscapes are rarely abrupt; thus, contour intervals of the bathymetric maps are commonly on the order of 20 to 30 cm. Using the contour maps and aerial photographs, the various landscape units within the mapping area are delineated. Landscape units in coastal systems include lagoon bottom, bay bottom, flood tidal delta, washover fan, inlet, and shoal (Schoeneberger and Wysocki, 2012; USDA-NRCS, 2016). Landscape units in freshwater lakes and ponds include submerged shoreline, lakebed, cove, and shoal (Bakken, 2012).

The bathymetric contour maps serve as the base maps for the subaqueous soil survey. The landscape unit is the primal factor in the delineation of soil distribution on the landscape. Each landscape unit should be visited in the field and a preliminary assessment done with a bucket auger and peat sampler. To develop initial metrics of soil variability within landscape units, larger units may need to be investigated at three or four random locations. Which units will need additional investigations will depend on the scale of mapping (order 1 or 2). Preliminary assessments can be used to establish initial soil-landscape relationships. Delineations that do not follow these relationships should be reassessed in the field, and additional delineations (soil polygons) added where appropriate. Representative soil types should be identified from the preliminary studies, and their locations established for vibracoring. Transects can be run across the largest units to assess variability within delineations. For stony or bouldery mapping units, a push probe can be used to quickly estimate boulders and stones and better identify boundaries between different phases.

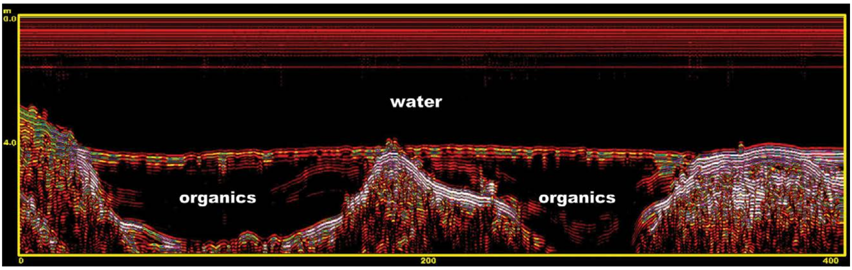
Remote Sensing

Although not necessary, several remote sensing tools can help improve mapping accuracy. In estuarine systems, side scan sonar is effective in identifying surface textures and features, such as stones, boulders, macroalgal cover, SAV, bottom type, and anthropogenic features (Oakley et al., 2012). The side scan is towed behind a boat sending signals in 25- to 50-m swaths. Transects are set apart by the size of the swath to ensure complete coverage. Soundings are recorded and translated in the lab with the appropriate software into a map showing the mosaic of swaths. Surface samples from preliminary soil survey efforts are used as ground truth for the signals that are mapped. Easily identifiable features from the side scan data include extent of stones or boulders and surface textures.

A simple tool that works well in areas with excellent water clarity (low turbidity) is the underwater video camera. The video camera can be towed slowly by the boat and tracked with a GPS. The images are projected onto a laptop. Points of interest (e.g., changes in surface texture or presence, absence, or abundance of coarse fragments or stones and boulders) are noted and the GPS coordinates recorded. Limitations for the video camera are the field-of-view and the possibility of fouling by algae or seagrasses. The field-of-view is often limited to a width of 25 cm because the camera needs to be close to the subaqueous soil surface to clearly observe it. Thus, many transects are necessary to delineate between two mapping units (e.g., soils with a high content of rock fragments and soils with a low content of rock fragments). The closer the camera is to the soil surface the more likely the lens will be fouled by detritus, algae, or seagrasses.

Ground-penetrating radar (GPR) can be invaluable in freshwater systems (it cannot be used in saltwater because the salts attenuate the signal). The GPR antenna can be towed slowly behind a boat in a rubber or plastic raft or across ice. GPR is effective at identifying surface and subsurface stones and boulders, shallow depths to lithic materials, and the depth and distribution of organic soil materials (fig. 10-8). Chapter 6 has additional information about the use of GPR in soil survey.

Figure 10-8



GPR output for a freshwater lake with thick organic materials. Water, mineral soil materials, and organic soil materials are easy to identify from the output.

Significance of Subaqueous Soil Information

Subaqueous soil survey interpretations can have a wide variety of uses. This section provides a few examples.

Water depth characteristics.—For use of a shallow water body, one of the most important spatial data layers is the bathymetry. Although bathymetric maps created for soil survey are not meant for navigation purposes (nautical charts include locations of buoys and other boating information), these maps can be used to understand the effects of storms on coastal systems or identify rapid changes in water depth for recreational purposes (mostly fishing). In most soil surveys of subaqueous soils, water depth is provided as a phase of each soil mapped (similar to slope phases in subaerial soil surveys). Although not perfect for navigation purposes, these data can help in identifying shallow areas boats should avoid or in identifying shallow areas suitable for wading activities, such as clamming.

Mitigation of dredging effects.—Areas of subaqueous soils in estuarine or freshwater settings are dredged to allow boats and ships to move freely in and out of the system or for the development and construction of marinas. Issues related to dredging are primarily disruption of the benthic ecology, re-release of the contaminants and nutrients in the soils, and disposal of the dredge materials. If the dredged materials are placed someplace in the water, another subaqueous area is disturbed. The dredging process alone may re-suspend nutrients or contaminants that are stored in the subaqueous soils. Pruett (2010) showed that soils with high fluidity (Hydrowassents) and soils with sulfidic materials (Sulfiwassents) contained significantly higher concentrations of heavy metals (Pb, Zn, As, Cu, and Cr) than simple soils (Haplowassents) and sandy soils (Psammowassents). Hydrowassents are typically finer textured and contain high levels of soil organic carbon. The soil organic carbon forms a complex with the metals in the water column, and the complex is later deposited on the soil surface. In Sulfiwassents, the metals may also complex with the sulfides. Pruett (2010) found in some cases that the metal concentrations in Sulfiwassents were high enough to negatively affect the benthic ecology. In freshwater systems, Bakken (2012) found that there were significant differences in P concentrations among soil types. Where extractable P concentrations were greater than 200 $\mu g\ g^{-1}$, there was a significantly greater chance of the presence of invasive plants such as milfoil and fanwort.

Commonly, the dredge materials are placed on the land surface. Knowing whether or not those materials contain contaminants or sulfides is critical to managing the dredge materials. When exposed to the air, sulfides will oxidize, release sulfuric acid, and may create acid sulfate conditions or soils. These acid sulfate soils may release metals if reaction approaches extremely acid (pH of 4 or 3). They are also extremely difficult to vegetate. Salisbury (2010) showed that soils in low-energy environments, such as coves, bayfloors, and lagoon bottoms, that contain high concentrations of sulfide may drop in pH from 7.5 to 3.0 in as little as 3 weeks following dredging and placement in an oxidized environment.

Suitability for moorings, docks, and other structures.—Surabian (2007) showed how subaqueous soil properties, primarily fluidity and depth of fluid soil materials, affect the types of moorings that can be used to secure boats. If the soil materials are non-fluid, heavy moorings are required. If they are fluid, mushroom-type moorings are used. Similarly, areas for docks require soil materials that are non-fluid and can support pilings.

Aquaculture.—Salisbury (2010) showed that certain subaqueous soils are more productive for aquaculture than others (in this study, hard shell clams and oysters). For example, an average of 58 percent of the oysters grown on sandy non-fluid soils reached harvestable size in two growing seasons while less than 12 percent of the oysters grown on soils dominated by sulfidic materials reached that size in the same period. Aquaculturists are now using subaqueous soil maps to identify new places to lease for growing oysters in coastal lagoons.

Ecological assessment and restoration.—Seagrasses such as eelgrass (*Zostera marina*) are an important component of the estuarine ecosystem. They provide several ecosystem functions and services, including trapping sediment and pollutants in the water column and serving as habitat for a variety of shellfish, finfish, shrimp, and other benthic fauna. Because eelgrass habitat has been declining worldwide, there have been numerous studies focused on eelgrass distribution and restoration. Restoration of eelgrass has been difficult, with an average success rate of 30 percent (Fonseca et al., 1998). Because a major issue is site selection (Calumpong and Fonseca, 2001), subaqueous soil surveys can provide spatial soil data to use in site selection models for eelgrass restoration.

Carbon accounting.—Another important current issue in soil science is carbon accounting. Subaqueous soils are typically not sampled and analyzed when carbon stocks are assessed. However, studies have shown that, although soil organic carbon concentration in subaqueous soils varies widely, some subaqueous ecosystems may have as much carbon as wetlands and forested ecosystems (Jespersen and Osher, 2007; Payne, 2007; Balduff, 2007; Pruett, 2010; Bakken, 2012). These potential sinks for carbon should be inventoried, characterized, and considered in regional carbon budgets.

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CHAPTER 11

Human-Altered and Human-Transported Soils

By John Galbraith, Virginia Polytechnic Institute and State University, and Richard K. Shaw, USDA-NRCS.

Introduction

This chapter is a practical guide for soil scientists conducting or interpreting a soil survey that includes human-altered and human-transported (HAHT) soils and materials. HAHT soils include soils that were intentionally and substantially modified by humans for an intended purpose, commonly for terraced agriculture, building support, mining, transportation, and commerce. They do not include soils modified through standard agricultural practices (such as shallow plowing, liming, and fertilization) or farmed soils with unintended wind and water erosion. Evidence for HAHT soils includes manufactured items (e.g., artifacts) present in the profile, human-altered material (e.g., deeply excavated or plowed soil) or human-transported material (e.g., fill), and position on or above anthropogenic landforms (e.g., flood-control levees) and microfeatures (e.g., excavator scrape marks). Detailed criteria regarding the identification of anthropogenic (artificial) landforms, human-altered material, and human-transported material are in the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014).

Using position on or above very specific anthropogenic landforms and features as a property of the soil for classification purposes is somewhat of a departure from past conventions for defining classes in Soil Taxonomy. However, landscape- and landform-related criteria have been used for the identification of Fluventic and Cumulic subgroups (i.e., slope) and for the plaggen epipedon (i.e., raised landforms). The use of specific kinds of anthropogenic landforms for HAHT soils is an extension of these precedents. Destructional and constructional anthropogenic (human-constructed) landforms and microfeatures (see chapter 2) have evident purpose and are undeniably linked to the soil itself. Linear straightening of waterways, drainage ditches, sanitary landfill mounds, and geometric shaped excavation features are all tied to extreme soil modification or compilation (fig. 11-1). Regardless of the characteristics of the soil, if a soil is on or above an anthropogenic landform or microfeature, it can definitely be associated with a human activity and assigned to a unique taxa. For example, it would be hard to deny that the soil on the large public landfills in figure 11-1 was transported by humans, whether manufactured items are found in the 2-meter profile or not. Historical records can provide additional supportive proof. The movement of soil by humans resets the soil-forming factor of time and commonly truncates or buries a more developed soil, thus strongly influencing soil properties. Soil development depends on all soil-forming processes, including those associated with the construction of the anthropogenic landform or microfeature.

Soils in urban areas are commonly human-transported (e.g., fill) or human-altered (e.g., truncated or mixed *in situ*) to significant depth. They generally exhibit a wide variety of conditions, and many are covered with impervious surfaces (e.g., buildings and pavements). The same situation occurs in suburban and low-density urban areas, but the proportion of less altered soils is higher and the proportion of buildings and pavements is lower. In many areas with HAHT soils, surface geomorphology and hydrology have been intensely altered. Other highly modified landscapes contain significant amounts of human-transported materials, such as steep farmland with closely spaced hillslope terraces (fig. 11-2) and areas of intense activity, such as mines, oilfields, and highway corridors. Spoils from land-leveling, filling, construction, mining, dredging, waste-disposal, and manufacturing operations become parent materials for new soils, which are commonly used to extend urban areas or airports into shallow water or to fill wetlands. Major areas of human-altered materials occur where agricultural areas have been deeply ripped to loosen impervious subsoil horizons, such as in the Central Basin of California. There is a need to identify, describe, and map HAHT soils because these soils have been modified enough from their original state that former soil maps do not provide the correct information or there is no information on them at all.

Background

Humans substantially modify or transform the physical, chemical, and biological properties and processes of the soil through anthropedogenesis (Richter and Yaalon, 2012). Because they can profoundly affect all five

Figure 11-1

Top image—This landfill complex (center-right) is a constructional anthropogenic landform that rises approximately 33 m higher than the surrounding lower coastal plain swamp near Virginia Beach, Virginia. The geometric shaped excavation pit (now a lake) is an associated destructional landform. Both landforms are out of context with surrounding soils and landforms. Bottom image—The anthropogenic landform can be confirmed with edaphic and documented evidence of methane-producing garbage and artifacts layered between a geotextile membrane and soil material. (Images by R. Facun and S. Early, courtesy of The Virginian-Pilot)

soil-forming factors (parent material, climate, organisms, time, and relief or topography), some authors (Dudal, 2005) have established a sixth factor, described as a "master variable capable of modifying or controlling the other five factors" (Amundson and Jenny, 1991). In particular, humans excavate deeply enough to remove most or all soil

Figure 11-2

Machu Picchu, Peru. HAHT soils can be identified not only by diagnostic features in the soil profile but also by their association with anthropogenic landforms, whether manufactured items are found in the profile or not. This ancient urban area has geometric hillslope terraces on cut-and-fill landforms (foreground and lower right) created by humans in mountainous terrain to allow grazing, farming, and house building on formerly steep slopes. It demonstrates intentional human modification and transportation of soil. (Photo by Pedro Szekely)

horizons, impart manufactured materials and debris (artifacts) that become included in soil parent materials (fig. 11-3), and transport and deposit extensive amounts of soil, rock, and sediment that become new parent materials.

Humans also level (cut and fill) large areas, destroying natural landforms and building anthropogenic landforms and microfeatures (e.g., drainage ditches) as described in chapter 2. Archaeological evidence shows that humans have been altering soils for at least 8,000 to 10,000 years. Soil alterations have been slight (surficial) and collateral to standard agricultural practices (e.g., erosion) or been intentional and profound (e.g., mountaintop mining and extensive landform alteration through terracing or oilfield activity). Extensively modified areas with integrated land management are called “anthroscapes” (Eswaran et al., 2005) (fig. 11-4).

Figure 11-3

Profile of the Laguardia soil series showing artifacts in multiple deposits of human-transported material. The buried building debris contains brick, concrete, wire, steel, and asphalt. (Photo by Richard Shaw)

Development of HAHT Soil Concepts in the U.S.

The effort to formally describe and classify HAHT soils began in 1988 with the formation of the International Committee for Anthropogenic Soils (ICOMANTH). This committee was commissioned by USDA's Soil Conservation Service to introduce differentiae and taxa for classification and survey of observed human-altered and human-transported soils (also called anthropogenic soils). The charge of the committee was to introduce HAHT soils into U.S. Soil Taxonomy, facilitate mapping of urban areas, introduce new terms and materials into USDA databases,

Figure 11-4

An ancient Roman urban anthroscape, which reminds us that humans have been purposely modifying and moving soil in urban areas for millennia (the Colosseum is at the back on the right). Modern urban anthroscapes often include a mosaic of water, parks, buildings, and pavements (roads and sidewalks). (Photo by Andreas Tille)

enable meaningful interpretations of unique materials and soils, and facilitate establishment and correlation of new soil series. Between 1995 and 2010, seven circular letters were distributed internationally for feedback on committee ideas. The International Field Tour of Anthropogenic Soils of Nevada and California in 1998; the 5th Soils of Urban, Industrial, Traffic and Mining Areas (SUITMA) tour held in New York City in 2009; and the 4th IUSS Conference for Soil Classification held in Lincoln, Nebraska, in 2012 were used to test proposals and solicit feedback from diverse groups. ICOMANTH proposals were reviewed, accepted, and published in the 11th and 12th editions of the *Keys to Soil Taxonomy* (Soil Survey Staff, 2010, 2014). Major outcomes were the identification of human-altered material, human-transported material, and manufactured items as differentiae at both the subgroup and family levels in Soil Taxonomy. In addition, standard terms and conventions for describing anthropogenic features (artifacts) in soil profiles, as well as additional horizon nomenclature for identifying horizons impacted by human activity, were adopted (see chapter 3).

Importance

The human impact on the global environment since the Industrial Revolution has been so profound that a new geological epoch—the "Anthropocene"—has been proposed (Crutzen and Steffen, 2003; Steffen et al., 2011). As the human population increases, so does the degree and amount of land alteration by humans. About 3 percent of world's land surface is classified as urban (CIESIN, 1995), and the percentage is increasing as more people move into cities, especially along coastlines, where 10 percent of the land is urban. As of 2011, approximately 82 percent of the U.S. population and 52 percent of the world's population lived in urban areas (United Nations, 2013). In many areas, humans grow food in or near heavily developed areas, in soils with undocumented or unpredictable properties. Human alteration of soil occurs worldwide. For example, humans are clearing land deep into South American jungles for agriculture and mining, thus driving settlement further north into previously undeveloped areas. Agriculture on modified soils occurs extensively on most continents. Rice is grown in human-irrigated and -flooded paddies (many of which are hillslope terraces) covering 153.7 million hectares (IRRI, 2010).

Little was previously known about the chemical and physical properties and behavior of profoundly altered soils. In the past, their classification was minimal because of high variability. For example, urban HAHT soils were commonly classified at higher taxa, such as Udorthents, and had almost no specific information in USDA databases to provide meaningful interpretations. In order to improve soil survey of HAHT soils, additional taxa were needed for their classification, new methods were needed for their analysis, and new terms were needed for describing their properties so that soil maps and proper interpretations for their use could be provided.

Resource Management Issues and HAHT Soils

Important uses of soil survey information in urban areas include restoration and revegetation efforts, hydrologic interpretations for stormwater management, urban agriculture, and resource inventory (e.g., to identify wetlands). Urban soil surveys are used to advocate for best use and management practices for open space areas.

Mined and drilled lands, farmlands, intensively used agricultural areas, and some urban areas contain contaminated HAHT soils. Now that over half of the world's population is in urban areas, soil-related health risks are increasingly important. Human health concerns occur from contact with or exposure to contaminated soils, many of which are HAHT soils. Soils may impact humans directly (e.g., dust inhalation or contact with bare feet) or indirectly (e.g., metal uptake by vegetables). Some highly contaminated soils are not safe for direct soil sampling except by trained and equipped specialists; less-contaminated soils are likely to be surveyed and mapped. Agricultural areas subject to heavy pesticide, herbicide, or fungicide application also have an adverse impact on soil water, surface water, and ground water. Developers, administrators, politicians, regulators, and planners need soil information in determining best management practices to protect water quality and public health. Potentially contaminated sites can be managed for human use. For example, some landfills and brownfields have been carefully constructed or reclaimed for use as parkland (Scheyer and Hipple, 2005; Craul, 1992, 1999).

Occurrence

HAHT soils occur on all continents, even Antarctica (fig. 11-5). They are common on intensively managed lands where humans have established civilizations, including some areas now underwater. New HAHT soils are being formed every day. In the future, HAHT soils may occur on other celestial bodies. There is no record on global distribution of HAHT soils besides maps using national classification systems or the World Reference Base for Soil Resources (IUSS, 2014). Although HAHT soils are global in extent, they are commonly unmapped, unrecognized, and underappreciated.

Identification

By definition, HAHT soils have profound and purposeful alteration or occur on landforms with purposeful construction or excavation. The alteration is of sufficient magnitude to result in the introduction of a new parent material (human-transported material) or a profound change in the previously existing parent material (human-altered material) (see chapter 2). HAHT soils do not include soils with incidental or unintentional surficial changes due to standard agricultural practices or the shallow incorporation of artifacts through plowing. For example, a soil that has higher pH, fertility, or base saturation due to standard practices does

Figure 11-5

McMurdo Station, Antarctica. Human alteration of landforms, relocation of soil for building of infrastructure, and alteration of soil profiles occur even in this remote location. (Photo by Alan Light)

not have long-term change, whereas a soil that was shaped into an agricultural conservation terrace is profoundly and intentionally altered for a long-term purpose. Some changes serve no useful purpose and can be judged as unintentional (e.g., cultivation can lead to wind or water erosion or salinization and discarded manufactured trash can end up in a plow layer).

Many classification systems, including the World Reference Base (IUSS, 2014) and Soil Taxonomy, recognize HAHT soils at the highest levels, as Anthosols and as Technosols and Anthosols, respectively. Soil Taxonomy presently recognizes HAHT soils with a combination of taxa at the subgroup and family levels. Features of these soils include:

- An anthropic or plaggen epipedon
- Material between 25 and 50 cm thick that meets all the requirements of a plaggen epipedon except thickness
- 50 cm or more of human-altered and human-transported material over the original soil material

- HAHT material comprising the entire soil above a root-limiting layer or a contact that is shallower than 50 cm

Soil properties and characteristics that are used for the identification of human-transported and human-altered material are given in chapter 3 of the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014) and are summarized below.

Human-Transported Material

Human-transported material (HTM) is soil parent material (organic or mineral) that has been moved horizontally onto a pedon from a source area outside of that pedon by purposeful human activity. Since constructional anthropogenic landforms are built with transported material, HTM is associated with these landforms. Commonly, a lithologic discontinuity or a buried horizon can be observed just below HTM. It may be difficult to distinguish human-transported material and parent material from mass movement processes (e.g., landslides) without intensive onsite examination and analysis. Evidence of HTM includes:

- Detached pieces of diagnostic horizons (such as argillic, calcic, histic, or spodic horizons) which are derived from the excavated source material
- Presence of artifacts such as brick, asphalt, glass, metal, plastic, combustion by-products, mechanically abraded rocks, midden material, and scrape marks
- Irregular distributions of artifacts or contaminants either with depth in the profile or with proximity away from an anthropogenic landform, feature, or constructed object, such as a road or building
- Lithologic discontinuities at the contact between HTM and the underlying former surface
- An underlying manufactured layer, such as a geotextile liner or concrete
- Location of the material on a constructional anthropogenic landform or microfeature or within the boundary of a destructional anthropogenic landform or microfeature

Human-Altered Material

Human-altered material (HAM) is soil parent material (organic or mineral) that has undergone anthroturbation (mixing or disturbance by humans). It differs from HTM in that it generally has been altered in place and contains little or no evidence of being transported from another location. Examples include agricultural soils that have been deeply mixed (e.g., by deep ripping of a root-restrictive subsoil layer such as a duripan) and soils that have been mechanically compacted to impound water (as in a rice paddy with anthric saturation). The concept also includes soils that have been removed, stockpiled, and replaced during reclamation (as in some surface mining or urban development activities) and soil materials that remain exposed after excavation (such as those on the floor of a gravel pit).

Human-altered materials are commonly associated with destructional anthropogenic landforms. These landforms are in areas where soil material has been removed (pits, quarries, mined areas, etc.). In some cases, a destructional landform may be recognized by tracing a subsurface horizon (such as an argillic or spodic horizon) from adjacent non-human-altered soils laterally to the point where it disappears abruptly, which corresponds to the boundary of the destructional landform.

Destructional anthropogenic landforms are excavated but may later be filled or covered. Where the excavations have been partially or totally filled with the original soil material, the material is considered HAM. Where they have been filled with different soil material, the material is considered HTM.

Evidence of human-altered material includes:

- Material occurs in an area impacted by the agricultural practices of deep plowing to rip a root-restrictve layer or of intentional compaction to puddle water.
- Material occurs within an excavated area (destructional landform) such as a pit or quarry.
- The soil profile has features such as reoriented pieces of diagnostic horizons; rock fragments that are mechanically abraded; scrape marks underlying soil material that was removed, stockpiled, and replaced on site; or purposely compacted layers formed during construction activities.

Manufactured Layers

A manufactured layer is an artificial, root-limiting layer below the soil surface. These layers can be identified by their presence in or on an anthropogenic landform or microfeature, ranging from landfills to concrete-lined ditches to ponds. The soil above is HAHT material. The layers are used in construction (e.g., roof of an underground building) or to impede water, gas, or roots (e.g., landfill liner). There is a contact with HTM at the top of the manufactured layer, typically made out of geotextile liners, asphalt, concrete, rubber, or plastic. Below the layer, there may be more HTM, a layer of human-altered material, natural soil material, or rock.

Description

HAHT materials are described using standard methodology and procedures as discussed in chapter 3. Many of the standard conventions are also used, but there are a few items unique to descriptions of human-transported and human-altered soil materials. These items are briefly summarized below. See chapter 3 for additional information.

Horizon Nomenclature Common to HAHT Soils

A caret symbol (^) is used as a prefix to the master horizon capital letter (e.g., ^A) for soil horizons or layers that formed in HTM. These materials are commonly at the current surface. In many archaeological sites, however, human-transported materials are buried by more recent materials or by naturally transported material.

A numerical prefix can be used in front of the caret symbol to indicate a discontinuity (e.g., ^A-2^C). The description of lithologic discontinuities is independent of the description of HAHT materials. It is not necessary to indicate a discontinuity at the contact between all HAHT material and the underlying material, but this can be done if the materials are significantly different and it helps in understanding the nature of the soil profile.

Horizons and layers of HAHT material containing artifacts are identified with both the caret as a prefix and the lowercase letter u as a suffix (e.g., ^Au). There is no minimum percentage volume of artifacts. Incidental trash (e.g., a windblown plastic grocery bag or discarded aluminum can) need not be described with a “u” unless indicative of purposeful deposition by humans.

Manufactured layers (i.e., liners) are identified with the master horizon capital letter M. There is a manufactured layer contact at the top. Recognized types of liners include geotextile liners, asphalt, concrete, rubber, and plastic. The caret symbol prefix is not used with “M.” Intentionally compacted soil may act as a liner, but since it is not industrially manufactured, it is indicated with the lowercase letter d as a suffix. The layer may be further identified as densic material and having a densic contact if it meets those criteria (Soil Survey Staff, 2014).

Artifacts

Artifacts are materials created, modified, or transported from their source by humans, typically for a practical purpose in habitation, manufacturing, excavation, agriculture, or construction activities (Soil Survey Staff, 2014). Artifacts may be particulate (< 2 mm in diameter) or discrete (≥ 2 mm in diameter in smallest dimension). Particulate artifacts cannot be estimated by sight or feel in the field and are measured on an oven-dried weight basis. They are not typically described until after lab measurement. Examples of discrete artifacts include bitumen (asphalt), brick, concrete, metal, paper, plastic, rubber, and treated or shaped wood products (see fig. 11-3). *Persistent artifacts* remain in the soil relatively unchanged for a decade or more. *Nonpersistent artifacts* undergo rapid weathering or decay and remain intact in the soil for only a few months or a few years. After burial, artifact properties may change over time. Their presence and their weathering by-products can significantly affect the physical and chemical properties of the soil. Some artifacts are considered noxious, such as arsenic-treated wood products, discarded batteries, petroleum products, and medical waste. Others are considered relatively innocuous, such as untreated wood products, iron, bricks, cinder blocks, and paper products. Knowing the nature and properties of artifacts can be very important in understanding the soil and in developing appropriate plans and strategies for land management. Because of their importance, kinds of artifacts are evaluated when assigning HAHT soils to taxonomic families in Soil Taxonomy (Soil Survey Staff, 2014).

Artifacts are described separately from rock fragments or other features in the soil. Descriptions of artifacts generally include quantity, degree of cohesion, persistence, size, and safety classes. They may also include shape, kind, penetrability by roots, and roundness. Other attributes may be described if considered useful in understanding and interpreting the soil. In addition, for soils containing more than 15 percent, by volume, artifacts, texture classes are modified with the adjective "artifactual." The terms and classes used to describe artifacts are provided in chapter 3.

Survey Methods and Procedures

Assessing Survey Needs

At the onset of an urban soil survey, its potential uses and audience need to be evaluated and the survey objectives established, including the type of information needed. Typical users include the municipal parks department; city, State, and Federal agencies; schools, colleges, and universities; and community groups. Environmental professionals in the urban community may be less familiar with soil survey and its applications. An advisory committee can be assembled to help identify users' needs, provide operational guidance and assist with land access, review survey progress, publicize the survey, and disperse information.

Reference Materials

Examples of Previously Completed Urban Soil Surveys

To date, urban soil surveys in the U.S. recognizing HAHT materials have been completed in San Diego (USDA-SCS, 1973); Washington, D.C. (USDA-SCS, 1976a); St. Louis (USDA-SCS, 1982); Baltimore (USDA-NRCS, 1998); Chicago (Web Soil Survey, 2013); New York City (Web Soil Survey, 2014); and Los Angeles (Web Soil Survey, 2017) and have begun in Los Angeles and Detroit. Other surveys on the urban fringe include Montgomery County, Maryland (USDA-NRCS, 1995); Essex (USDA-NRCS, 2007b) and Hudson (Web Soil Survey, 2012) Counties in New Jersey; Plymouth County, Massachusetts (Web Soil Survey, 2010); and Fairfax County, Virginia (Web Soil Survey, 2011). Other soil surveys covered human-altered soils in the Central Valley of California (USDA-NRCS, 2003), mined lands in coalfields, and heavily terraced lands across the United States. These soil surveys can provide examples and ideas when planning new surveys in similar urban areas. Soil survey updates commonly need to remap tracts of more recently developed land. Even though some profoundly altered areas exceed the minimum size of a map unit, many are correlated to the original soil series, are correlated as miscellaneous land types, or occur in map units such as "Udorthents-Urban land complex" or "Area not mapped." There is a high demand for information about these areas. As the work to conduct soil surveys in urban areas progressed over the nearly 50 years represented by the above examples, the understanding of human-altered and human-transported soils improved and the way these soils are described, classified, and mapped also advanced greatly. Consulting examples of previously completed urban soil surveys, especially those that used the most recent advances in this area, is the first step in planning new urban soil survey projects.

Other Ancillary Resource Materials

Urban areas include a variety of land uses, e.g., inner city or urban cores, industrial and residential areas, cemeteries, parks, and other open spaces. Pouyat et al. (2010) refer to an "urban soil mosaic," where the natural landscape has been fragmented into parcels with distinctive disturbance and management regimes and, as a result, distinctive characteristic soil properties. Where HAHT materials occur to a significant extent, an understanding is needed of pre-development conditions and land use history throughout the area. Topographic maps, including older maps from libraries and agencies, can be used to locate natural landforms and significant anthropogenic alterations. Archival aerial photography can help in identifying land use changes. Older soil or surficial geology maps can help in determining the nature of pre-existing parent material (which can also serve as local fill) and/or substratum conditions and may help in initial delineation of the survey area. These maps can also indicate the location of formerly wet or stony areas or other "undesirable" areas buried under human-transported materials in highly altered landscapes. Records of transportation departments (municipal, State, and Federal), along with landfill and dredging records from various departments, may provide valuable information. Municipal boring logs (e.g., those of the Department of Design and Construction, NYC) can serve as valuable data points in documenting the nature and thickness of HTM. Records from onsite soil investigations can provide field notes or pedon descriptions. Information from adjacent areas, especially those with similar geologic and soil conditions, is also useful. Publications of news articles, scientific reports, theses and dissertations, and documents from city agencies and historical societies commonly contain valuable information on the age and origin of HTM. The thorough collection and review of existing information in the area before the first hole is dug will save time and effort in the long run.

Mapping Scale

The challenge of mapping soils in urban areas is that severe disturbance and fragmentation of the land create high spatial variability that is beyond the scope of standard survey methods. For example, HTM may change across an area no larger than one pedon, as when a truckload of material is moved in. In this case, there are no polypedons to constitute a soil map unit. Order 1 surveys (see chapter 4) can offer 0.2-hectare level of detail (close to lot-sized) but may be time- and cost-prohibitive if routine soil survey methods are used. Small yards in residential areas, narrow transportation corridors, and soils in small commercial zones, medians, and parking lots are typically better suited to onsite inspections. However, the larger open spaces (more than a hectare) generally exhibit more uniformity in soil conditions because they have been disturbed less, or, if they have been subject to alteration and filling, consist of similar materials filled at the same time. They are generally easier to survey than small residential parcels. In addition, there is generally more demand for soils information on the larger areas for management, restoration, and resource inventory purposes.

Mapping scales for initial soil surveys in urban areas in the U.S. have ranged from 1:24,000 for San Diego, St. Louis, and Los Angeles to 1:12,000 for Washington, D.C., Baltimore, Chicago, and New York City. The soil survey of South Latourette Park in New York State consisted of 130 hectares mapped at a scale of 1:6,000. It served as a pilot project for modern soil mapping in New York City (USDA-NRCS, 1997). A general, or reconnaissance, soil survey at a scale of 1:62,500 was also conducted in New York City (USDA-NRCS, 2005) to provide a general guide to soil patterns around the city and serve as the foundation for more detailed future surveys. Order 1, high-intensity surveys include the Gateway National Recreation Area (USDA-NRCS, 2006) at 1:4,800, a scale that was compatible with other natural and cultural resource mapping and assessment by the National Park Service, and the Bronx River Watershed (USDA-NRCS, 2007a) at 1:6,000, which emphasized hydrologic applications and stormwater management. The complexity of soil patterns, the high value of the land and its intensive use, and the number of taxpayers potentially affected by better land use and management decisions in urban areas all favor a larger mapping scale. The primary considerations when selecting a mapping scale, however, are the survey objectives, the users' needs, the size of the survey area, and the time requirements.

Designing Taxonomic and Mapping Units

Soils in HAHT materials present a formidable challenge to soil survey; spatial and vertical variability can be complex and unpredictable, and soil conditions commonly change with little variation in landscape or vegetation. The variability in HAHT soil properties needs to be examined, along with the consistency and extent of various soil types. Certain HAHT soil types or human-altered landforms may be associated with a particular surficial geology type, landscape position, or pre-existing soil map unit and so allow for some soil-landscape modeling. In addition, the objectives of the survey need to be kept in mind when establishing differentiating criteria for soil components because some soil properties will vary with land cover and land use. Although important properties and ratings, such as saturated hydraulic conductivity (K_{sat}), hydrologic soil group, content of soil organic matter, pH, and nutrient content, can vary widely across the entire urban landscape, the range in these properties is generally much narrower within a specific land use.

Characterization and classification of HAHT soils will vary according to mapping scale. It has evolved somewhat with successive urban and suburban mapping efforts. Earlier surveys used miscellaneous areas (e.g., “Made land,” in the 1973 soil survey of San Diego Area by USDA-SCS) and the great group level, commonly Udorthents. The Washington D.C. survey (USDA-SCS, 1976a) mapped 11 phases of Udorthents. It had no ratings or interpretations for these phases, but some selected samples were listed in tables of physical and chemical properties. The Baltimore survey (USDA-NRCS, 1998) included six phases of Udorthents with some ratings. A minimum set of physical and chemical properties, approximating the series level of classification, is useful for many applications and suitable for most interpretations.

Defining Soil Series and Phases for HAHT Soils

The use of soil series for HAHT soils began in the 1970s. It has included strip-mining spoils in Haskell County, Oklahoma (USDA-SCS, 1975), dredge materials in Wagoner County, Oklahoma (USDA-SCS, 1976b), cut-and-fill soils in St. Louis (USDA-SCS, 1982), and deep-ripped, chemically altered soils in California’s Central Valley (USDA-NRCS, 2003). For these HAHT soils, the user has a complete set of estimated properties, ratings, and interpretations. The survey of New York City’s South Latourette Park (USDA-NRCS, 1997) featured five new series for HAHT soils, using artifact content in the > 2 mm fraction as one of the differentiating criteria. Soil Taxonomy uses amount and kinds of artifacts in the definitions of some family-level classes (Soil Survey Staff, 2014). Artifact content is also used by the World Reference Base for Soil Resources to define the Technosols reference soil group and the Technic and Hypertechnic (second-level) qualifiers (IUSS, 2014). The legend for the initial New York City survey (2014) included 29 HAHT soil series. Significant amounts of fill and waste materials serve as soil parent materials in this area. The Los Angeles survey included HAHT series; fill, landscaped, and graded phases at the great group, subgroup, and series levels; and some Urban land phases based on land use (i.e., commercial, residential, and industrial). This survey area extended beyond the city into areas of suburban and industrial land use, and human-altered landforms and landscapes were common.

Miscellaneous Areas

The miscellaneous area “Urban land” has long been used in soil survey as a map unit component. Because the definition of Urban land is somewhat ambiguous, the term has been used inconsistently. A miscellaneous area, by definition, is not soil. However, the Urban land component includes soil in some soil surveys. To avoid confusion, the New York City soil survey proposed a "Pavement and buildings" miscellaneous area because it was more descriptive. Ideally, such a miscellaneous area is restricted to actual impervious surfaces (e.g., an Urban land consociation would have 85 percent or more impervious surface). Delineating these areas and adding a substratum phase based on a surficial geology or predevelopment soil map, or adding a land use phase to the consociation, may provide additional information of value to the user (Efflend and Pouyat, 1997). The additional information would be especially important if the covered material was saturated or posed a risk of subsidence or a health hazard to humans (e.g., covered unregulated landfills).

Quantifying and describing the extent of impervious surfaces typically is done using geographic information system (GIS) tools or on aerial photographs or high-resolution satellite imagery. Other techniques use a dot grid. Impervious surfaces include sidewalks, rooftops, driveways, bridges, paved roads, and parking lots, excluding those known to be pervious (e.g., special materials, gravel, or packed soil).

Map Unit Design

Urban land is also frequently mapped in complex with HAHT soils and minimally altered soils. Several different complexes may be needed to reflect lot sizes and percent composition of Urban land. For example, in the initial soil survey of New York City, less than 10 percent Urban land in a map unit was considered an inclusion. In areas with 10 to 49 percent impervious surface, Urban land was named as a major component of a map unit complex, and in areas with 50 to 90 percent impervious surface, Urban land was named as the dominant component of the complex. Areas with over 90 percent Urban land were named as a map unit consociation, with the type of original surface identified (e.g., glacial till, outwash, tidal marsh) as a substratum phase. Other human-altered miscellaneous areas include Dumps, Oil-waste land, Pits, Quarries, Scoria land, and Slickens.

Classification

As discussed above, soil series can be defined for HAHT soils where the human-induced processes leading to their formation are relatively uniform over mappable areas (e.g., deep ripping, replacement of stockpiled soils after mining, placement of uniform fill material, and extensive subsoil compaction for flood irrigation). When surveying an area, new soil series should be developed for predictably recurring soils that have a significant amount or type of HAHT material, undergo deep alteration of hydrology (anthraquic saturation), or are deeply excavated. Existing series may need to be reclassified or areas resurveyed to recognize HAHT soils.

To properly classify HAHT soils, descriptions of HAHT soil profiles need to document the kind and amount of HAHT soil materials and the kind and amount of artifacts present and to recognize the presence of diagnostic horizons and features (such as an anthropic or plaggen epipedon, anthric saturation, and densic materials). Soil Taxonomy (Soil Survey Staff, 2014) recognizes various taxa for HAHT soils at the subgroup and family levels. These taxa are listed in tables 11-1 and 11-2 along with a brief statement about the concept for the taxa and its general occurrence. There will likely be additional taxa in the future.

Table 11-1

Soil Taxonomy Subgroups and HAHT Soil Concepts

Subgroup	General concept
Anthraquic	Soils have a currently or formerly ponded surface due to flood irrigation, commonly with puddled or compacted horizons that hold water near the surface. They commonly occur in rice paddies and aquaculture areas.
Anthrodensic	Soils have a constructed densic contact due to human activity. They commonly occur in reclaimed mined lands and building or transportation construction sites.
Anthropic	Soils have an anthropic epipedon. They occur in many areas associated with sustained human habitation or cultivation.
Plaggic	Soils have a plaggen epipedon (50 cm or more of plaggen material). They mostly occur in northern Europe. They may also be associated with some intensive organic farming operations.
Haploplaggic	Soils have 25 to 49 cm of plaggen materials. They mostly occur in northern Europe. They may also be associated with some intensive organic farming operations.
Anthroportic	Soils formed in parent material that was transported by humans (HTM). They occur worldwide.
Anthraltic	Soils formed in parent material that was altered in place by humans. They mainly occur in intensely cultivated areas and in areas of burials or trenching.

HAHT soils may be further identified at the family level by the presence of unusual materials anywhere in the upper 2 m that are not geologic in nature. The HAHT family classes explained in table 11-2 are inserted between particle-size class and mineralogy class for soils that qualify for HAHT subgroups, that have at least 50 cm of HAHT material on top, or for which the whole soil above a root-limiting layer or contact occurring at a depth shallower than 50 cm is HAHT materials.

Table 11-2

Soil Taxonomy Family Terms and HAHT Soil Concepts

Family term	General concept
Methanogenic	Soils produce ≥ 1.6 ppb methane or methyl mercaptan. They occur in landfills and waste-disposal sites. They do not include natural anaerobic environments.
Asphaltic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 35% (by volume) asphalt (bitumen) ≥ 2 mm in diameter. They occur in fill areas with construction debris, on top of old impervious surfaces, in landfills, and near highway paving projects.
Concretic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 35% (by volume) concrete ≥ 2 mm in diameter. They occur in fill areas with construction debris, on top of old impervious surfaces, in landfills, and near construction projects.
Gypsifactic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 40% (by weight) synthetic gypsum products, commonly as drywall or flue gas desulfurization gypsum. They occur in fill areas with construction debris, in landfills, and near building projects.
Combustic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 35% (by volume) coal combustion by-products ≥ 2 mm in diameter and too heavy to be volatile (e.g., bottom ash or coal slag). They occur in approved disposal areas, unregulated fill sites, city parks, and gravel-topped roads in urban areas.
Ashifactic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 15% (by grain count in the 0.02 to 0.25 mm fraction) light-weight, coal combustion by-products that are volatile, such as fly ash. They typically occur in approved disposal sites, unregulated fill sites, and retention ponds near power plants.

Table 11-2.—continued	
Family term	**General concept**
Pyrocarbonic	Soils have a layer ≥ 7.5 cm thick that contains ≥ 5% (by grain count in the 0.02 to 0.25 mm fraction) light-weight products of pyrolysis, such as fuel coke or biochar. They typically occur in approved disposal sites, unregulated fill sites, and retention ponds and near power plants. They include terra preta soils.
Artifactic	Soils contain ≥ 35% discrete artifacts ≥ 2 mm that are both persistent and cohesive in a layer ≥ 50 cm thick. They typically occur in landfills, fill areas, and transportation corridors.
Pauciartifactic	Soils contain ≥ 15% (up to 35%) discrete artifacts ≥ 2 mm that are both persistent and cohesive in a layer ≥ 50 cm thick. They typically occur in landfills, fill areas, urban areas, construction sites, and transportation corridors.
Dredgic	Soils contain finely stratified (≤ 5 cm thick) layers of dredged or irrigated sediment in a layer ≥ 50 cm thick. They occur on anthropogenic landforms near a dredged source, in tailing ponds, and in agricultural fields flood-irrigated with diverted stream water.
Spolic	Soils contain ≥ 50 cm of HTM. They mainly occur on anthropogenic landforms, in clean fill areas, and in artificially landscaped areas.
Araric	Soils contain a layer ≥ 7.5 cm thick with ≥ 3% (by volume) mechanically detached and re-oriented pieces of diagnostic horizons or characteristics. They mainly occur in intensely managed agricultural fields, burial grounds, excavated borrow and mine pits, transportation corridors, and flood-irrigated rice and fish production areas.

Additional Soil Survey Information

More than easy-to-understand map unit descriptions and a special symbols legend are important in conveying soil survey information for urban and other highly modified areas. Block diagrams, soil profile and landscape photos, a glossary, explanation figures, and catena tables with drainage class by parent material can also be used. For example, the soil survey of South Latourette Park in New York City included a series of colorful cartoon-like soil profile drawings. Soil-system type block diagrams depicting water movement through the environment are particularly useful for stormwater management and hydrologic modeling.

Field Operations

The degree of parcelization of the landscape that is common in urban and suburban areas can create problems with survey site access. Establishment of good relations with parks department personnel; property managers in golf courses, cemeteries, and schools and colleges; and other environmental professionals is typically very beneficial. Utility companies and city engineering and parks departments should be contacted to find out if any soil excavations are planned in the survey area. Open gravesites in cemeteries can provide access to natural soil materials. Construction sites and street excavations provide opportunities to observe substratum characteristics.

The following points should be considered when surveying human-altered landscapes:

1. A preliminary examination of the original topography, landform, surficial materials, or soil types, as well as the land use history, should precede any site investigations.
2. Historical maps, records, and vintage photographs should be gathered and related to current mapping resources before and during mapping.
3. Familiarity with the parent material and soil properties in an area helps in determining whether a particular pedon is human-altered or -transported.
4. A characterization, classification, or delineation of the site beforehand is generally helpful. Depending upon the survey objectives and map unit design, these soil lines can reflect pre-existing natural landforms, human-altered landforms, current land use or land cover patterns, or some combination of these. The traverse across the initially delineated area will determine soil uniformity.
5. Highly contrasting soils should be differentiated if possible, with transecting to determine map unit composition.
6. Chemical properties of human-transported soils, particularly when enriched with artifacts, can be significantly different than those of soils in naturally occurring materials.
7. Predictions of soil-landscape associations eventually become evident. For example, certain vegetation types occur with

undisturbed soils and certain human-transported soils occur with certain parent materials or landscape positions.

8. Generally, the location of human-transported soils is somewhat logical. For example, areas with undesirable soil conditions are used for waste disposal. In disturbed areas, however, predictions need more verification than in undisturbed areas.
9. Conventional mapping protocol generally may be followed and modified when encountering anthropogenic landforms, unusual or abrupt changes in parent material, miscellaneous land types, or small areas of contrasting soil.
10. The location of buried utilities, such as gas lines, fiber optic cable, water pipes, etc., must be ascertained before digging.

Topography, Landforms, and Anthropogenic Features

Many constructional and destructional anthropogenic landforms and microfeatures are listed in the *Keys to Soil Taxonomy* (Soil Survey Staff, 2014). Additionally, the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2012) provides a list of anthropogenic (earth-surface) features, ranging in size from entire landscapes to bioswales and road cuts. Anthropogenic landscapes, or anthroscapes, are human-modified with substantial and permanent alterations. Anthropogenic landforms are large enough to delineate at commonly used map scales (1:24,000 to 1:10,000). They can be grouped as constructional (e.g., fill) or destructional (e.g., excavated). Anthropogenic microfeatures are features that formed at the surface by purposeful human activity and are too small to delineate at commonly used map scales (1:24,000 to 1:10,000). Included with microfeatures are what archaeologists call "anthropogenic features," which do not occupy three-dimensional volume (e.g., scrape marks of machinery), and temporal forms too small to map at any scale (e.g., plowed ridges and furrows).

The British Geological Society has established a hierarchical classification system for mapping "artificial ground classes" (Rosenbaum et al., 2003). At the upper level of this classification, there are five genetic subdivisions: made ground, worked ground, infilled ground, disturbed ground, and landscaped ground. They are followed by a topographic/geographical category (e.g., embankment, waste heap) and finally a material or lithologic type (e.g., building rubble, rock waste). Consideration of these or similar classes may be helpful in understanding HAHT soils.

Equipment Needs

Because compacted soils, sharp objects, cobble- and stone-sized artifacts, and rock fragments are common in urban areas, digging equipment should include heavy-duty tools, such as a reinforced metal shovel and a large metal bar. Conventional soil survey equipment is also needed, along with recent maps and locational equipment, such as cell phones or GPS units. Soil quality (soil health) testing equipment is needed for special project areas and should include soil tests that relate to ecosystem functions and services. Portable field equipment for measuring pH, conductivity, total dissolved solids, bulk density, infiltration, saturated hydraulic conductivity, and heavy metals should be taken on survey trips.

Rapid and non-invasive geophysical methods have great potential for use in urban soil survey (see chapter 6). Ground-penetrating radar (GPR) can provide information on depth to or thickness of human-transported or contrasting materials, buried tanks or drums, etc. Electromagnetic induction (EMI) has been used to assess differences in soil water content, compaction, texture, lithology, mineralogy, pH, $CaCO_3$ content, soil organic carbon, and other soil properties. Magnetic susceptibility can be used to identify industrial dusts and certain types of artifacts (Howard and Orlicki, 2015) and as a proxy for trace metal levels in soil (Yang et al., 2012). Portable X-ray fluorescence (PXRF) spectrometers can determine trace metal contents in the field and assess spatial variability. Most of these methods require some initial investigation (to determine their suitability) and some calibration. However, when considering the time needed for hand digging pits in urban areas and the extent of lateral and vertical variability in some fill materials, they may be deemed practical. Chapter 6 has a more extensive discussion of non-invasive tools.

Safety Precautions in Urban Areas

In urban areas, hazardous materials (HazMat) training is advisable. Maps of known Superfund and brownfield sites should be taken to the field. *Superfund* is a U.S. Federal government program designed to fund the cleanup of sites contaminated with hazardous substances and pollutants. A brownfield is a property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant (US-EPA, 2016). PXRF meters should be used in suspected brownfield areas, unregulated landfills, and hazardous waste areas for the safety of surveyors.

Heavy-duty gloves, hard-toed boots, and hardhats should also be used in some areas. Traffic cones should be used to prevent accidents while parking or pausing vehicles. Utility companies must be contacted before digging to prevent accidents. Surveyors should set known check-in times and have a plan in case of traffic delays or late arrival. Using prepaid bridge and tunnel passes saves time and money.

Surveyors should work in pairs; carry cell phones, walkie-talkies, and whistles; and wear uniforms with insignia or obvious lettering (e.g., New York City Soil Survey) and identification badges. Cars should have a magnetic car door logo or other markings clearly identifying their official purpose. In urban areas, it is important not to look vulnerable, e.g., surveyors should show evidence that they are connected to a protected and respected group and can summon help quickly. Surveyors should avoid areas with vagrants unless accompanied by authorities, avoid trespassing into high-security areas, and recognize dangerous parts of urban areas. Exposure to drug sales or manufacturing, marijuana gardens, gang violence, sexual attack, and racism and other discriminatory actions may pose a real threat in certain urban areas. Surveyors should not carry valuables, other than essential identification, in the field or in the vehicle. They should take proper precaution in dark areas and at night. Rabies and animals infected by rabies, insects, snakes, and dogs are abundant in urban areas, as are poisonous plants.

Pedon Descriptions

Most pedon properties are described according to conventional standards. Exceptions are defined earlier in this chapter. Two representative pedon descriptions of HAHT soils are provided below.

Laguardia Series

The Laguardia series consists of very deep, well drained soils. These soils formed in a thick mantle of construction debris intermingled with human-transported soil materials. They occur on modified landscapes in and near major urbanized areas of the Northeast. Slope ranges from 0 to 75 percent. Saturated hydraulic conductivity is low to moderately high. Mean annual temperature is about 13 degrees C, and mean annual precipitation is about 1196 mm.

Taxonomic Classification: Loamy-skeletal, artifactic, mixed, superactive, nonacid, mesic Anthropic Udorthents

^Au—0 to 20 cm; brown (10YR 4/3) artifactual coarse sandy loam, pale brown (10YR 6/3) dry; weak very fine subangular blocky structure; friable; few very fine and medium roots; 15 percent cobble-sized brick and concrete fragments, 5 percent cobble-sized asphalt fragments, 5 percent gravel-sized glass fragments, and 5 percent natural cobbles; neutral (pH 7.2); gradual wavy boundary.

^BCu—20 to 66 cm; brown (10YR 4/3) very artifactual coarse sandy loam; weak very fine subangular blocky structure; friable; few very fine roots; 25 percent cobble-sized brick and concrete fragments, 5 percent cobble-sized asphalt fragments, 5 percent cobble-sized metal fragments, 5 percent gravel-sized plastic fragments, and 5 percent natural cobbles; neutral (pH 7.2); gradual wavy boundary.

^Cu—66 to 200 cm; brown (10YR 4/3) very artifactual coarse sandy loam; massive with compaction-related plate-like divisions; very friable; few very fine roots; 25 percent cobble-sized brick and concrete fragments, 10 percent cobble-sized asphalt fragments, 5 percent cobble-sized metal fragments, 5 percent gravel-sized glass fragments, 5 percent gravel-sized plastic fragments, and 7 percent natural cobbles; neutral (pH 7.2).

Ladyliberty Series (fig. 11-6)

The Ladyliberty series consists of very deep, moderately well drained soils with moderately low to moderately high saturated hydraulic conductivity. These soils formed in a thick mantle of human-transported material consisting of coal slag, dredged materials, and/or any geologic deposits ranging from till, outwash, alluvium, or coastal plain sediments (typically from a local source). They occur on anthropogenic landforms in and near major urbanized areas of the Northeast. Slope ranges from 0 to 8 percent. Mean annual temperature is about 13 degrees C, and mean annual precipitation is about 1196 millimeters.

Taxonomic Classification: Sandy-skeletal, combustic, mixed, mesic Anthropic Udorthents

^Au—0 to 5 centimeters; very dark grayish brown (10YR 3/2) fine sandy loam; weak medium granular structure; very friable; many very fine to coarse roots throughout; 10 percent gravel-sized coal slag fragments; strongly acid (pH 5.2); clear wavy boundary. (5 to 27 centimeters thick)

^ABu—5 to 16 cm; dark yellowish brown (10YR 3/4) artifactual loam; moderate medium subangular blocky and moderate fine granular structure; friable; common fine roots around fragments; 15 percent coarse subangular gravel-sized coal slag and 2 percent gravel-sized fine wire, bed springs, and glass; strongly acid (pH 5.2); abrupt smooth boundary.

2^Cu1—16 to 39 cm; black (7.5YR 2.5/1) very artifactual loamy sand; massive; loose; few fine roots within cracks; 25 percent gravel-sized subangular coal slag and brick, 20 percent gravel-sized wood, and 2 percent gravel-sized wire; slightly acid (pH 6.2); abrupt smooth boundary.

2^Cu2—39 to 65 cm; strong brown (7.5YR 4/6) extremely artifactual loamy sand; massive; firm; 70 percent gravel-sized subangular coal slag; slightly acid (pH 6.4); abrupt smooth boundary.

3^C1—65 to 96 cm; dark yellowish brown (10YR 4/4) gravelly sand; massive or single grain; loose; 20 percent well rounded fine gravel and 2 percent shell fragments; neutral (pH 6.8); abrupt smooth boundary.

3^C2—96 to 167 cm; dark brown (10YR 3/3) sand; massive or single grain; loose to firm; 2 percent well rounded fine gravel; slightly alkaline (pH 7.8); abrupt smooth boundary.

3^Cg1—167 to 185 cm; very dark gray (10YR 3/1) sand; single grain; loose; 2 percent well rounded fine gravel; slightly alkaline (pH 7.8); abrupt smooth boundary.

4Cg2—185 to 200 cm; very dark gray (N 3/) silt loam; massive; firm; strongly alkaline (pH 8.6).

Figure 11-6

A profile of the Ladyliberty soil series (similar to the one described in the text). Multiple deposits of human-transported materials overlie a naturally deposited gleyed substratum at a depth of 120 cm. The upper 16 cm consists of transported topsoil over transported coal slag with artifacts. Beneath the coal slag, at a depth of 55 cm, is a dredged spoil deposit. (Photo by Richard Shaw)

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APPENDIX 1

Official Soil Series Description

The descriptions, maps, and information in the appendices were generated using publically accessible websites developed and supported by the USDA Natural Resources Conservation Service. They are examples of the soil survey products discussed in this manual. These products are developed and delivered to the public with the integrated use of standardized procedures, terminology, technologies, and data systems in a cooperative environment that includes Federal, State, and local units of government and universities (i.e., the National Cooperative Soil Survey).

The appendices provide examples of four main pillars of soil survey information: (1) official soil series descriptions (OSDs), (2) detailed map unit descriptions, (3) the National Cooperative Soil Survey Soil Characterization Database, and (4) Web Soil Survey.

The OSD database is the national collection of more than 20,000 detailed soil series descriptions from across the U.S. and its territories. The OSDs are managed in a text format following specific standards for organization and content. The name of a soil series is the common reference term used in the name of soil map units. Soil series are the most homogenous classes in Soil Taxonomy. The descriptions contain soil properties that define a specific soil series and distinguish it from other soil series and serve as the basis for the taxonomic classification.

As an example, the official description of the Olton series follows.

Olton Series

Location, Olton: TX+NM
Established Series
Rev. TCB-JKA-RM
08/2016

The Olton series consists of very deep, well drained, moderately slowly permeable soils that formed in clayey, calcareous eolian sediments in the Blackwater Draw Formation of Pleistocene age. These soils are on nearly level to gently sloping plains and upper side slopes of playas and draws. Slope ranges from 0 to 5 percent. Mean annual precipitation is 483 mm (19 in), and mean annual temperature is 15 degrees C (59 degrees F).

TAXONOMIC CLASS: Fine, mixed, superactive, thermic Aridic Paleustolls

TYPICAL PEDON: Olton clay loam, on a northeast-facing, convex, 2 percent slope in cropland at an elevation of about 1,120 m (3,675 ft.). (Colors are for dry soil unless otherwise stated.)

A—0 to 20 cm (0 to 8 in); brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; moderate medium granular and subangular blocky structure; hard, friable; many fine roots; common fine pores; common earthworm channels; common wormcasts; neutral; gradual smooth boundary. (15 to 36 cm [6 to 14 in] thick)

Bt1—20 to 38 cm (8 to 15 in); brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; moderate fine and medium subangular blocky structure; very hard, firm; common fine roots; few fine pores and root channels; few distinct clay films on faces of peds; slightly alkaline; gradual wavy boundary. (10 to 25 cm [4 to 10 in] thick)

Bt2—38 to 79 cm (15 to 31 in); reddish brown (5YR 5/4) clay loam, reddish brown (5YR 4/4) moist; moderate medium angular blocky structure; very hard, firm; few fine roots, mostly between peds; earthworm channels and casts; few distinct clay films on faces of peds; noneffervescent in upper part; few films and threads of calcium carbonate at a depth of about 22 inches, slightly effervescent; moderately alkaline; gradual wavy boundary. (20 to 41 cm [8 to 16 in] thick)

Btk1—79 to 122 cm (31 to 48 in); reddish brown (5YR 5/4) clay loam, reddish brown (5YR 4/4) moist; weak medium angular blocky structure; very hard, firm; common fine root channels and pores; few distinct clay films on faces of peds; about 5 percent fine films and threads of calcium carbonate; violently effervescent; moderately alkaline; clear wavy boundary. (38 to 66 cm [15 to 26 in] thick)

Btk2—122 to 191 cm (48 to 75 in); pink (5YR 7/3) clay loam, light reddish brown (5YR 6/4) moist; weak medium angular blocky and subangular blocky structure; hard, firm; about 35 percent fine and medium calcium carbonate masses and medium and coarse calcium carbonate concretions and nodules; violently effervescent; moderately alkaline; diffuse wavy boundary. (25 to 91 cm [10 to 26 in] thick)

Btk3—191 to 251 cm (75 to 99 in); red (2.5YR 5/6) clay loam, red (2.5YR 4/6) moist; weak very coarse prismatic structure parting to moderate medium subangular blocky; very hard, firm; few distinct clay films on faces of peds and clay bridged sand grains; common soft to weakly cemented films of calcium carbonate, amount decreases with depth and is less than 2 percent in lower part of horizon; strongly effervescent ped surfaces, some noneffervescent ped interiors; moderately alkaline.

TYPE LOCATION: Randall County, Texas; from the intersection of U.S. Highways 87 and 60 in Canyon, 8.9 kilometers (5.5 miles) west on U.S. Highway 60, about 2.4 kilometers (1.5 miles) north on county road, 966 meters (0.6 mile) east and 644 m (0.4 mile) north in cultivated field or 854 m (2,800 ft.) east and 488 m (1,600 ft.) north of SE corner of sec. 7, Block 1. T. T. R. R. Survey; latitude: 35 degrees, 01 minute, 28 seconds N; longitude: 102 degrees, 01 minute, 03 seconds W; Bivins Lake, Texas USGS quad; NAD27.

RANGE IN CHARACTERISTICS: Soil moisture: An ustic moisture regime bordering on aridic. The soil moisture control section is dry in some or all parts for more than 180 but less than 205 days, cumulative, in normal years. July through August and December through February are the driest months. These soils are intermittently moist in September through November and March through June.

Mean annual soil temperature: 15 to 18 degrees C (59 to 64 degrees F)
Depth to argillic horizon: 15 to 36 cm (6 to 14 in)
Depth to secondary carbonates: 36 to 71 cm (14 to 28 in)
Depth to calcic horizon: 76 to 152 cm (30 to 60 in)
Solum thickness: more than 203 cm (80 in)
Particle-size control section: 35 to 50 percent silicate clay

A horizon:
Hue: 5YR to 10YR
Value: 3 to 5, 2 to 4 moist
Chroma: 2 or 3
Texture: Loam, clay loam
Effervescence: None to slight
Reaction: Neutral to moderately alkaline

Bt horizons:
Hue: 5YR or 7.5YR
Value: 3 to 5, 2 to 4 moist
Chroma: 2 to 6

Texture: Clay loam, clay
Visible calcium carbonate: Few films and threads at about 56 cm (22 in)
Effervescence: None to slight
Reaction: Slightly alkaline or moderately alkaline

Btk horizons:
Hue: 2.5 to 7.5YR
Value: 5 to 7, 4 to 6 moist
Chroma: 3 to 8
Texture: Clay loam, silty clay loam
Visible calcium carbonate: 15 to 60 percent as masses, films, threads, concretions, and nodules
Effervescence: Violent
Reaction: Moderately alkaline or strongly alkaline

B′t horizon below the calcic (where present):
Hue: 2.5YR to 7.5YR
Value: 5 to 7, 4 to 6 moist
Chroma: 3 to 8
Texture: Loam, sandy clay loam, clay loam
Visible calcium carbonate: Few threads, films, and nodules
Effervescence: Slight or strong
Reaction: Moderately alkaline or strongly alkaline

COMPETING SERIES: There are no other series in this family. Similar soils include the Acuff, Estacado, Pullman, and Pantex series.

Acuff series: Has 18 to 35 percent silicate clay in the particle-size control section.

Estacado series: Is calcareous in upper horizons and has 20 to 35 percent silicate clay in the particle-size control section.

Pantex and Pullman series: Have COLE of more than 0.06.

GEOGRAPHIC SETTING:
Parent material: Clayey, calcareous eolian sediments in the Blackwater Draw Formation of Pleistocene age
Landform: Nearly level to gently sloping plains and upper side slopes of playas and draws
Slopes: Dominantly less than 3 percent, but can range up to 5 percent
Mean annual air temperature: 14 to 17 degrees C (57 to 62 degrees F)
Mean annual precipitation: 432 to 533 mm (17 to 21 in)
Frost-free period: 180 to 220 days
Elevation: 793 to 1,524 m (2,600 to 5,000 ft.)
Thornthwaite annual P-E Index values: 30 to 34

GEOGRAPHICALLY ASSOCIATED SOILS: These are the similar Acuff, Estacado, and Pullman series and also the Amarillo, Pep, and Portales series.

- Acuff, Amarillo, and Estacado soils: Are in landscape positions similar to those of the Olton series and average less than 35 percent clay in the particle-size control section.
- Pep soils: Are in landscape positions similar to those of the Olton series and do not have an argillic horizon.
- Portales soils: Are in slightly lower landscape positions and average less than 35 percent clay in the particle-size control section.
- Pullman soils: Are in landscape positions similar to those of the Olton series and have COLE of more than 0.06.

DRAINAGE AND PERMEABILITY: Well drained. Moderately slow permeability. Runoff is low where slopes are 0 to 1 percent and medium where slopes are 1 to 5 percent.

USE AND VEGETATION: Mainly cultivated for cotton, sorghum, and winter wheat. A considerable acreage is irrigated. Climax native vegetation is dominantly shortgrasses with a few midgrasses and includes blue grama and buffalograss. Also included are lesser amounts of vine-mesquite, western wheatgrass, sideoats grama, galleta, tobosa, silver bluestem, wild alfalfa, and prairie clover. This soil has been correlated to the Deep Hardland (077CY022TX) range site in MLRA 77C.

DISTRIBUTION AND EXTENT: Southern High Plains, Southern Part (MLRA 77C in LRR H) of western Texas and eastern New Mexico. The series is extensive.

MLRA SOIL SURVEY REGIONAL OFFICE (SSRO) RESPONSIBLE: Temple, Texas

SERIES ESTABLISHED: Lamb County, Texas; 1960.

REMARKS: This is a Benchmark Series.

Diagnostic horizons and features recognized in this pedon are:

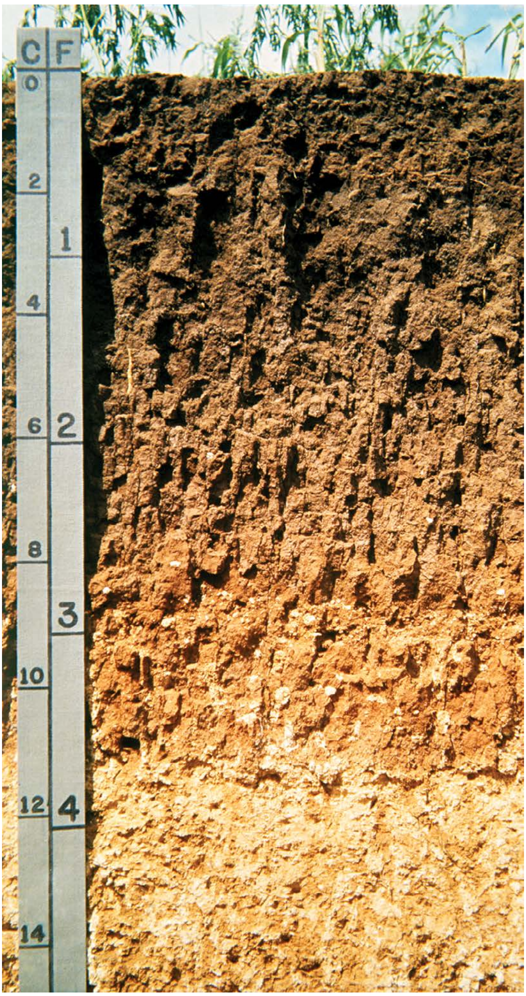
- Mollic epipedon: 0 to 38 cm (0 to 15 in) (A, Bt1 horizons)
- Argillic horizon: 20 to 251 cm (8 to 99 in) (Bt1, Bt2, Btk1, Btk2, Btk3 horizons)
- Calcic horizon: 79 to 191 cm (31 to 75 in) (Btk1, Btk2 horizons)

ADDITIONAL DATA: NSSL Characterization data: Sample Nos. S78TX-381-001 and S90TX-381-001, 001A, 001B, 001C, 001D

(Randall Co.); S81TX-069-001 (Castro Co.); S90TX-359-001, 001A, 001B, 001C, 001D (Oldham Co.); S81TX-069-001 and S93TX-069-001 (Castro Co.); and S92TX-369-001, 001B, 001C, 001D, 001E, 001F and S96TX-369-001, 002 (Parmer Co.). USDA-ARS Bulletin B-1727 "Olton Soils, Distribution, Importance, Variability and Management" 4-98, Paul W. Unger and Fred B. Pringle.

Taxonomic Version: Keys to Soil Taxonomy, Twelfth Edition, 2014.

Figure A-1



Profile of the Olton series.

APPENDIX

2

Detailed Map Unit Description

The following map unit description is typical of those produced by the Web Soil Survey (WSS). Note that for ease of use by the public in the U.S., metric units have been converted to English units.

OcA—Olton clay loam, 0 to 1 percent slopes

Map Unit Setting

National map unit symbol: f5sv
Elevation: 2,800 to 5,000 feet
Mean annual precipitation: 17 to 21 inches
Mean annual air temperature: 57 to 63 degrees F
Frost-free period: 185 to 220 days
Farmland classification: Prime farmland if irrigated

Map Unit Composition

Olton and similar soils: 85 percent
Minor components: 15 percent
Estimates are based on observations, descriptions, and transects of the map unit.

Setting

Landform: Plains
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Clayey eolian deposits from the Blackwater Draw Formation of Pleistocene age

Typical profile

Ap - 0 to 8 inches: clay loam
Bt - 8 to 31 inches: clay loam
Btk1 - 31 to 48 inches: clay loam
Btk2 - 48 to 80 inches: clay loam

Properties and qualities

Slope: 0 to 1 percent

Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained
Runoff class: Low
Capacity of the most limiting layer to transmit water (K_{sat}): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Calcium carbonate, maximum in profile: 50 percent
Salinity, maximum in profile: Nonsaline (0.0 to 1.0 mmho/cm)
Sodium adsorption ratio, maximum in profile: 1.0
Available water storage in profile: Moderate (about 8.9 inches)

Interpretive groups
Land capability classification (irrigated): 2e
Land capability classification (nonirrigated): 3e
Hydrologic soil group: C
Ecological site: Deep Hardland 16-21″ PZ (R077CY022TX)
Hydric soil rating: No

Minor Components

Pullman soils
Percent of map unit: 7 percent
Landform: Plains
Down-slope shape: Linear
Across-slope shape: Linear
Ecological site: Deep Hardland 16-21″ PZ (R077CY022TX)
Hydric soil rating: No

Acuff soils
Percent of map unit: 5 percent
Landform: Plains
Down-slope shape: Linear
Across-slope shape: Linear
Ecological site: Deep Hardland 16-21″ PZ (R077CY022TX)
Hydric soil rating: No

Estacado soils
Percent of map unit: 3 percent
Landform: Plains
Down-slope shape: Linear
Across-slope shape: Linear
Ecological site: Deep Hardland 16-21″ PZ (R077CY022TX)
Hydric soil rating: No

Appendix 3

NCSS Soil Characterization Database

The National Cooperative Soil Survey (NCSS) Soil Characterization Database contains the analytical results from the Kellogg Soil Survey Laboratory (KSSL) at the National Soil Survey Center (NSSC) in Lincoln, Nebraska, as well as the results from numerous cooperating State university laboratories in the United States. Properties measured in the laboratory serve as the basis for interpretations related to soil use and management. Standardized methodologies and procedures used in the laboratory are contained in the *Kellogg Soil Survey Laboratory Methods Manual*, Soil Survey Investigations Report (SSIR) No. 42 (by the Soil Survey Staff). The KSSL data are provided in reports (for example, Primary and Supplementary Characterization Data Sheets) and are available in various electronic forms, including online, tape, CD, and DVD.

The database includes pedons that represent the central concept of a soil series, pedons that represent the central concept of a map unit but not of a series, and pedons sampled to bracket a range of properties within a series or landscape. Not all analyses are conducted for every soil. Suites of analytical procedures are run based upon anticipated or known conditions regarding the nature of the soil being analyzed. Results are reported in tiers. For example, soils of arid environments are routinely analyzed for salts and carbonates as part of the standard analysis suite. Tables A-1 and A-2 show some of the primary characterization data and supplemental data for a pedon of Olton series sampled in Castro County, Texas, in 2006.

Table A-1

Primary Characterization Data

*** Primary Characterization Data ***

Pedon ID: S2006TX069003 (Castro, Texas)

Sampled as on Mar 29, 2006: Olton; Fine, mixed, superactive, thermic Calcic Haplustert
Revised to correlated: Olton; Fine, mixed, superactive, thermic Aridic Paleustolls

United States Department of Agriculture
Natural Resources Conservation Service
National Soil Survey Center
Kellogg Soil Survey Laboratory
Lincoln, Nebraska 68508-3866

SSL - Project C2006USNL085 MLRA 77D
- Site ID S2006TX069003 Lat: 34° 20’ 54.50” north Long: 102° 10’ 55.09” west MLRA: 77D
- Pedon No. 06N0716
- General Methods 1B1A, 2A1, 2B

Layer	Hori-zon	Orig Hzn	Depth (cm)	Field Label 1	Field Label 2	Field Label 3	Field Texture	Lab Texture
06N02986	Ap	Ap	0-12	S06TX069-003-1			CL	CL
06N02987	Bt1	Bt1	12-27	S06TX069-003-2			C	CL
06N02988	Bt2	Bt2	27-48	S06TX069-003-3			C	CL
06N02989	Btk	Btk	48-99	S06TX069-003-4			SCL	CL
06N02990	Btkk1	Btkk1	99-125	S06TX069-003-5			CL	C
06N02991	Btkk2	Btkk2	125-203	S06TX069-003-6			CL	CL

Pedon Calculations

Calculation Name	Result	Units of Measure
LE, Whole Soil, Summed to 1m	6	cm/m

PSDA & Rock Fragments				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
					(- - - - Total - - - - -)			(- - Clay - - -)		(- - - Silt - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)					(Rock Fragments (mm))				
				Lab	Clay	Silt	Sand	Fine	CO_3	Fine	Coarse	VF	F	M	C	VC	(- - - - Weight - - - - -)				>2 mm
				Text-	<	.002	.05	<	<	.002	.02	.05	.10	.25	.5	1	2	5	20	.1-	wt %
	Depth			ure	.002	-.05	-2	.0002	.002	-.02	-.05	-.10	-.25	-.50	-1	-2	-5	-20	-75	75	whole
Layer	(cm)	Horz	Prep		(- % of <2mm Mineral Soil -)												(- - - % of <75mm - -)				soil
					3A1a1a			3A1a1a	3A1a1a	3A1a1a		3A1a1a	3A1a1a	3A1a1a	3A1a1a	3A1a1a					
06N02986	0-12	Ap	S	cl	31.8	37.9	30.3	22.5		13.9	24.0	16.8	11.2	2.2	0.1	tr	--	--	--	14	--
06N02987	12-27	Bt1	S	cl	32.7	36.8	30.5	25.1		14.5	22.3	16.8	11.5	2.1	0.1	--	--	--	--	14	--
06N02988	27-48	Bt2	S	cl	39.0	33.9	27.1	28.8		13.8	20.1	13.8	11.4	1.9	tr	--	--	--	--	13	--
06N02989	48-99	Btk	S	cl	36.9	33.0	30.1	16.0	1.3	11.9	21.1	14.7	12.3	2.7	0.2	0.2	1	tr	--	16	1
06N02990	99-125	Btkk1	S	c	41.3	38.1	20.6	9.4	30.7	25.4	12.7	10.4	7.9	2.0	0.2	0.1	2	2	tr	14	4
06N02991	125-203	Btkk2	S	cl	38.3	40.3	21.4	9.7	24.5	26.7	13.6	10.8	8.4	1.7	0.3	0.2	1	2	--	13	3

Bulk Density & Moisture				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-
				(Bulk Density)		Cole	(--------------Water Content-------------)						WRD	Aggst		
				33	Oven	Whole	6	10	33	1500	1500 kPa	Ratio	Whole	Stabl	(Ratio/Clay)	
	Depth			kPa	Dry	Soil	kPa	kPa	kPa	kPa	Moist	AD/ OD	Soil	2-0.5mm	CEC7	1500 kPa
Layer	(cm)	Horz	Prep	(- - - g cm^{-3} - - -)			(- - - - - - - - % of < 2mm - - - - - - - ---)						cm^3 cm^{-3}	%		
				DbWR1	DbWR1				DbWR1	3C2a1a		3D1				
06N02986	0-12	Ap	S	1.27	1.52	0.062			25.0	13.3		1.036	0.15		0.62	0.42
06N02987	12-27	Bt1	S	1.39	1.71	0.072			25.6	14.2		1.039	0.16		0.62	0.43
06N02988	27-48	Bt2	S	1.39	1.73	0.076			26.9	16.0		1.045	0.15		0.61	0.41
06N02989	48-99	Btk	S	1.48	1.74	0.055			22.8	14.9		1.044	0.12		0.56	0.40
06N02990	99-125	Btkk1	S	1.43	1.50	0.016			22.8	9.3		1.017	0.19		0.17	0.23
06N02991	125-203	Btkk2	S	1.50	1.63	0.028			18.8	9.6		1.019	0.13		0.21	0.25

Carbon & Extractions				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-
				(- - - - - Total - - - - -)			Est	OC	C/N	(Dith-Cit Ext)			(- - - - Ammonium Oxalate Extraction - - - -)						(-Na Pyro-Phosphate-)			
	Depth			C	N	S	OC	(WB)	Ratio	Fe	Al	Mn	Al+½Fe	ODOE	Fe	Al	Si	Mn	C	Fe	Al	Mn
Layer	(cm)	Horz	Prep	(- - - - - % of <2 mm - - - - - -)						(- - - - - - - - - - - - - - % of < 2mm - - - - - - - - - - - - - -)								mg kg^{-1}	(- - - % of < 2mm - - -)			
				4H2a	4H2a	4H2a				4G1	4G1	4G1		4G2	4G2	4G2	4G2	4G2				
06N02986	0-12	Ap	S	1.18	0.13	tr	1.2		9	0.9	0.1	tr	--	0.02	--	--	--	--				
06N02987	12-27	Bt1	S	0.65	0.09	tr	0.6		7	0.9	0.1	tr	0.13	0.02	0.08	0.09	0.06	268.3				
06N02988	27-48	Bt2	S	0.63	0.09	--	0.6		7	1.1	0.1	tr	0.16	0.02	0.09	0.12	0.07	249.2				
06N02989	48-99	Btk	S	0.69	0.09	--	0.3		4	1.0	0.1	tr	0.13	0.01	0.06	0.10	0.06	215.4				
06N02990	99-125	Btkk1	S	6.93	0.09	--	0.4		5	0.3	--	--	0.02	0.01	0.01	0.02	0.02	9.8				
06N02991	125-203	Btkk2	S	6.11	0.03	0.01	0.2		5	0.3	--	--	0.02	0.01	0.01	0.02	0.02	15.1				

CEC & Bases				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10--	-11-	-12-	-13-	-14-
				(- - - - - NH_4OAC Extractable Bases - - - -)								CEC8	CEC7	ECEC		(- -- - Base - - - -)	
								Sum	Acid-	Extr	KCl	Sum	NH_4	Bases	Al	(-- Saturation --)	
	Depth			Ca	Mg	Na	K	Bases	ity	Al	Mn	Cats	OAC	+Al	Sat	Sum	NH_4OAC
Layer	(cm)	Horz	Prep	(- - - - - - - - - - - - - - - - cmol(+) kg^{-1} - - - - - - - - - - - - - - - - -)							mg kg^{-1}	(- - - - cmol(+) kg^{-1} - - -)				(- --- - - % - -- - --)	
				4B1a1a	4B1a1a	4B1a1a	4B1a1a		4B2b1a1					4B1a1a			
06N02986	0-12	Ap	S	13.0*	6.3	--	1.9	21.2	3.2			24.4	19.6			87	100
06N02987	12-27	Bt1	S	14.6*	5.9	--	1.1	21.6	2.4				20.4				100
06N02988	27-48	Bt2	S	18.6*	7.0	0.1	0.9	26.6	2.4				23.7				100
06N02989	48-99	Btk	S	50.2*	6.9	0.2	0.8	58.1					20.7				100
06N02990	99-125	Btkk1	S	45.6*	3.7	0.3	0.4	50.0					7.2				100
06N02991	125-203	Btkk2	S	46.4*	3.1	0.3	0.5	50.3					8.1				100

*Extractable Ca may contain Ca from calcium carbonate or gypsum. CEC7 base saturation set to 100.

Salt				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-	-20-
				(- - - Water Extracted From Saturated Paste - - -)																	1:2		
																			Total	Elec	Elec	Exch	
	Depth			Ca	Mg	Na	K	CO_3	HCO_3	F	Cl	PO_4	Br	OAC	SO_4	NO2	NO_3	H_2O	Salts	Cond	Cond	Na	SAR
Layer	(cm)	Horz	Prep	(--- mmol(+) L^{-1} - -)				(- - - mmol(-) L^{-1} - - -)										(- - % - - -)		(- - dS m^{-1} - -)		%	
				4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2		4F2	4F1a1a1		
06N02986	0-12	Ap	S	2.5	1.6	0.3	0.6	--	3.7	--	0.7	tr	--	--	0.6	tr	0.1	56.3	--	0.52	0.28	--	tr
06N02987	12-27	Bt1	S																		0.24	--	
06N02988	27-48	Bt2	S																		0.19	tr	
06N02989	48-99	Btk	S																		0.18	1	
06N02990	99-125	Btkk1	S																		0.23	5	
06N02991	125-203	Btkk2	S	2.1	0.8	3.2	0.2	--	1.7	0.2	2.0	--	--	--	2.8	tr	tr	43.1	tr	0.72	0.29	2	3

pH & Carbonates				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-
				(- - - pH - - -)						(- - Carbonate - -)		(- - Gypsum - - -)		
					$CaCl_2$					As $CaCO_3$		As $CaSO_4$*$2H_2O$		Resist
	Depth				0.01M	H_2O	Sat			<2mm	<20mm	<2mm	<20mm	ohms
Layer	(cm)	Horz	Prep	KCl	1:2	1:1	Paste	Oxid	NaF	(- - - % - - -)				cm^{-1}
					4C1a2a	4C1a2a	4F2			4E1a1a1a1				
06N02986	0-12	Ap	S		6.8	7.1	7.1							
06N02987	12-27	Bt1	S		7.3	7.6				tr				
06N02988	27-48	Bt2	S		7.5	7.8				tr				
06N02989	48-99	Btk	S		7.8	8.2				3				
06N02990	99-125	Btkk1	S		7.9	8.5				54				
06N02991	125-203	Btkk2	S		7.8	8.3	8.0			49				

Phosphorous				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-
					(- - - - - - - -	- - - - - - - -	- - - - - - - -	Phosphorous	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -)	KCl
				Melanic	NZ	Acid	Anion Exch	Resin	Bray	Bray	Olsen	H_2O	Citric	Mehlich	Extr
	Depth			Index		Oxal	Available	Capacity	1	2			Acid	III	NO_3
Layer	(cm)	Horz	Prep		%	(- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	mg kg^{-1}	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -)
					4D8a1	4G2									
06N02986	0-12	Ap	S		14	--									
06N02987	12-27	Bt1	S		18	82.2									
06N02988	27-48	Bt2	S		23	54.5									
06N02989	48-99	Btk	S		25	40.0									
06N02990	99-125	Btkk1	S		78	113.7									
06N02991	125-203	Btkk2	S		87	109.0									

Clay Mineralogy (<.002 mm)				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
					X-Ray				Thermal						Elemental					EGME	Inter
													SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	Retn	preta
	Depth		Fract	7A1a1																	tion
Layer	(cm)	Horz	ion	(- - - - -	- peak size - -	- - -)	(- -	- - %	- -	- - -)			(- - - - -	- - - - -	- - - - %	- - - - -	- - - - -	- - - - -	- - - - -)	mg g^{-1}	
06N02986	0.0-12.0	Ap	tcly	MI 3	KK 2	QZ 1															CMIX
06N02988	27.0-48.0	Bt2	tcly	KK 2	QZ 1																CMIX
06N02991	125.0-203.0	Btkk2	tcly	CA 3	MI 1	KK 1															CMIX

FRACTION INTERPRETATION:

tcly - Total Clay <0.002 mm

MINERAL INTERPRETATION:

CA Calcite KK Kaolinite MI Mica QZ Quartz

RELATIVE PEAK SIZE: 5 Very Large 4 Large 3 Medium 2 Small 1 Very Small 6 No Peaks

INTERPRETATION (BY HORIZON):
CMIX - Mixed Clay

Sand - Silt Mineralogy (2.0-0.002 mm)				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
					X-Ray				Thermal							Optical				EGME	Inter
													Tot Re			Grain Count				Retn	preta
	Depth		Fract													7B1a2					tion
Layer	(cm)	Horz	ion	(- -- - peak size - - - -)					(-- - - - % - - - -- -)				(- - - - - - - - - - - -- - - - - - - % -- - - - - - - - - - - - - - - -)							mg g^{-1}	
06N02987	12.0-27.0	Bt1	csi										89	QZ 83	FK 8	CD 3	OP 2	PR 2	FE 1		SMIX
														PO tr	TM tr	ZR tr	FP tr	GN tr	GS tr		
														HN tr	MS tr	AR tr	BT tr	BY tr	CB tr		

FRACTION INTERPRETATION:
csi - Coarse Silt 0.02-0.05 mm

MINERAL INTERPRETATION:

AR Weatherable Aggregates	BT Biotite	BY Beryl	CB Carbonate Aggregates	CD Chert (Chalcedony
FE Iron Oxides (Goethite	FK Potassium Feldspar	FP Plagioclase Feldspar	GN Garnet	GS Glass
HN Hornblende	MS Muscovite	OP Opaques	PO Plant Opal	PR Pyroxene
QZ Quartz	TM Tourmaline	ZR Zircon		

INTERPRETATION (BY HORIZON):
SMIX - Mixed Sand

Table A-2

Supplementary Characterization Data

*** Supplementary Characterization Data ***

Pedon ID: S2006TX069003 (Castro, Texas)

Sampled as on Mar 29, 2006: Olton; Fine, mixed, superactive, thermic Calcic Haplustert
Revised to correlated: Olton; Fine, mixed, superactive, thermic Aridic Paleustolls

SSL - Project C2006USNL085 MLRA 77D
- Site ID S2006TX069003 Lat: 34° 20' 54.50" north Long: 102° 10' 55.09" west MLRA: 77D
- Pedon No. 06N0716
- General Methods 1B1A, 2A1, 2B

United States Department of Agriculture
Natural Resources Conservation Service
National Soil Survey Center
Kellogg Soil Survey Laboratory
Lincoln, Nebraska 68508-3866

Tier 1				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-	-20-	-21-	-22-	-23-	-24-	-25-
				(- - - - - - - - - - - - - - - - - Engineering PSDA - - - -- - - - - - - - - - - - - - - -)													(------ Cumulative Curve Fractions -----) (<75mm)								(Atter- berg)		(Gradation)	
				Percentage Passing Sieve													USDA Less Than Diameters (mm) at										Uni- fmty	Cur- vtur
	Depth			3	2	3/2	1	3/4	3/8	4	10	40	200	20	5	2	1.	.5	.25	.10	.05	60	50	10	LL	PI		
Layer	(cm)	Horz	Prep	(---------------Inches--------------					)	(------Number-------			)	(----Microns---		)	(---------Millimeter----------				)	(-----Percentile---		)	(----%---	)	CU	CC
06N02986	0-12	Ap	S	100	100	100	100	100	100	100	100	99	80	46	37	32	100	100	98	87	70	0.03	0.024	tr			83.7	0.2
06N02987	12-27	Bt1	S	100	100	100	100	100	100	100	100	99	80	47	38	33	100	100	98	86	70	0.03	0.022	tr			83.7	0.2
06N02988	27-48	Bt2	S	100	100	100	100	100	100	100	100	100	81	53	44	39	100	100	98	87	73	0.03	0.013	tr			76.9	0.1
06N02989	48-99	Btk	S	100	100	100	100	100	100	100	99	98	77	48	41	37	99	99	96	84	69	0.03	0.022	tr			88.9	0.1
06N02990	99-125	Btkk1	S	100	100	100	100	100	99	98	96	95	82	64	49	40	96	96	94	86	76	0.01	0.005	tr			38.2	0.3
06N02991	125-203	Btkk2	S	100	100	100	100	100	99	98	97	96	82	63	47	37	97	97	95	87	76	0.02	0.006	tr			41.0	0.3

Tier 2				-26-	-27-	-28-	-29-	-30-	-31-	-32-	-33-	-34-	-35-	-36-	-37-	-38-	-39-	-40-	-41-	-42-	-43-	-44-	-45-	-46-	-47-	-48-	-49-	-50-
				(- - - Weight Fractions - - -)														(- - - Weight Per Unit Volume (g cm^{-3})- - -)									(--Void---)	
				Whole Soil (mm)								<75 mm Fraction						Whole Soil				<2 mm Fraction					Ratios	
				>2	250	250	75	75	20	5		75	75	20	5			Soil Sur		Engineering		Soil Survey			Engineering		At 33 kPa	
	Depth				-UP	-75	-2	-20	-5	-2	<2	-2	-20	-5	-2	<2		33	Oven	Moist	Satur	33	1500	Oven	Moist	Satur	Whole	<2
Layer	(cm)	Horz	Prep	(--- % of Whole Soil ---)								(---- % of <75 mm -----)						kPa	-dry		-ated	kPa DbWR1	kPa	-dry DbWR1		-ated	Soil	mm
06N02986	0-12	Ap	S	--			--	--	--	--	100	--	--	--	--	100		1.27	1.52	1.59	1.79	1.27	1.41	1.52	1.59	1.79	1.09	1.09
06N02987	12-27	Bt1	S	--			--	--	--	--	100	--	--	--	--	100		1.39	1.71	1.75	1.87	1.39	1.56	1.71	1.75	1.87	0.91	0.91
06N02988	27-48	Bt2	S	--			--	--	--	--	100	--	--	--	--	100		1.39	1.73	1.77	1.87	1.39	1.56	1.73	1.76	1.87	0.91	0.91
06N02989	48-99	Btk	S	1			1	--	tr	1	99	1	--	tr	1	99		1.49	1.75	1.83	1.93	1.48	1.59	1.74	1.82	1.92	0.78	0.79
06N02990	99-125	Btkk1	S	4			4	tr	2	2	96	4	tr	2	2	96		1.46	1.53	1.78	1.91	1.43	1.47	1.50	1.76	1.89	0.82	0.85
06N02991	125-203	Btkk2	S	3			3	--	2	1	97	3	--	2	1	97		1.51	1.64	1.78	1.94	1.50	1.57	1.63	1.78	1.93	0.75	0.77

Tier 3				-51-	-52-	-53-	-54-	-55-	-56-	-57-	-58-	-59-	-60-	-61-	-62-	-63-	-64-	-65-	-66-	-67-	-68-	-69-	-70-	-71-	-72-	-73-	-74-	-75-
				(- - - Volume Fractions - - -)													C	(- - - Ratios To Clay - - -)					(-- Linear Extensiblity --)				(---WRD---)	
				Whole Soil (mm) At 33 kPa													/N	<2 mm Fraction					Whole Soil		<2 mm		Whole	<2
				>2	250	250	75	75	20	5		2-	.05-	LT	Pores		Rat	Fine	CEC		1500	LEP	33 kPa		to %		Soil	mm
	Depth				-UP	-75	-2	-20	-5	-2	<2	.05	.002	.002	D	F	-io	Clay	Sum	NH_4-OAC	kPa	33	1500	Oven	1500	Oven		
Layer	(cm)	Horz	Prep	(--- % of Whole Soil ---)															Cats		H_2O	kPa	kPa	-dry	kPa	-dry	(--in^3/in^3---)	
06N02986	0-12	Ap	S	--	--	--	--	--	--	--	100	14	18	15	20	32	9	0.71	0.77		0.42	0.195	3.5	6.2	3.5	6.2	0.15	0.15
06N02987	12-27	Bt1	S	--	--	--	--	--	--	--	100	16	19	17	12	36	7	0.77			0.43	0.220	3.9	7.2	3.9	7.2	0.16	0.16
06N02988	27-48	Bt2	S	--	--	--	--	--	--	--	100	14	18	20	10	38	7	0.74			0.41	0.195	3.7	7.6	3.9	7.6	0.15	0.15
06N02989	48-99	Btk	S	1	--	--	1	--	--	1	99	17	18	21	10	34	4	0.43			0.40	0.149	2.4	5.5	2.4	5.5	0.12	0.12
06N02990	99-125	Btkk1	S	2	--	--	2	tr	1	1	98	11	20	22	13	32	5	0.23			0.23	0.039	0.9	1.6	0.9	1.6	0.19	0.19
06N02991	125-203	Btkk2	S	1	--	--	2	--	1	1	99	12	23	21	16	27	5	0.25			0.25	0.073	1.5	2.8	1.5	2.8	0.13	0.14

Tier 4				-76-	-77-	-78-	-79-	-80-	-81-	-82-	-83-	-84-	-85-	-86-	-87-	-88-	-89-	-90-	-91-	-92-	-93-	-94-	-95-	-96-	-97-	-98-
				(- - - - - - - - - - - - - - - - - Weight Fractions - Clay Free - - - - - - - - - - - - - - - - - -)															Text -ure by PSDA	PSDA (mm)			pH Ca Cl2 .01M	Elect.		Part- -icle Den- sity
				(------------ Whole Soil -------------)						(---------------- <2 mm Fraction ----------------)										Sand	Silt	Clay		Res- ist. ohms	Con- duct dS m^{-1}	
				>2	75 -20	20 -2	2- .05	.05- .002	< .002	(------------ Sands -----------) VC	C	M	F	VF	(-- Silts -) C	F	Cl ay			2- .05	.05- .002	< .002				
Layer	Depth (cm)	Horz	Prep	(--- % of >2 mm Sand and Silt ---)						(-----------------% of Sand and Silt -------------)									<2 mm	(---- % of 2 mm ----)			(-------- <2 mm ------)			g cm^{-3}
																						3A1a1a	4C1a2a		4F2	
06N02986	0-12	Ap	S	--	--	--	44	56	47	--	tr	3	16	25	35	20	47		cl	30.3	37.9	31.8	6.8		0.52	
06N02987	12-27	Bt1	S	--	--	--	45	55	49	--	tr	3	17	25	33	22	49		cl	30.5	36.8	32.7	7.3			
06N02988	27-48	Bt2	S	--	--	--	44	56	64	--	--	3	19	23	33	23	64		cl	27.1	33.9	39.0	7.5			
06N02989	48-99	Btk	S	2	2	2	47	51	58	tr	tr	4	19	23	33	19	58		cl	30.1	33.0	36.9	7.8			
06N02990	99-125	Btkk1	S	7	7	7	33	61	66	tr	tr	3	13	18	22	43	70		c	20.6	38.1	41.3	7.9			
06N02991	125-203	Btkk2	S	5	5	5	33	62	59	tr	tr	3	14	18	22	43	62		cl	21.4	40.3	38.3	7.8		0.72	

APPENDIX

4

Web Soil Survey

By Kenneth Scheffe and Soil Science Division Staff.

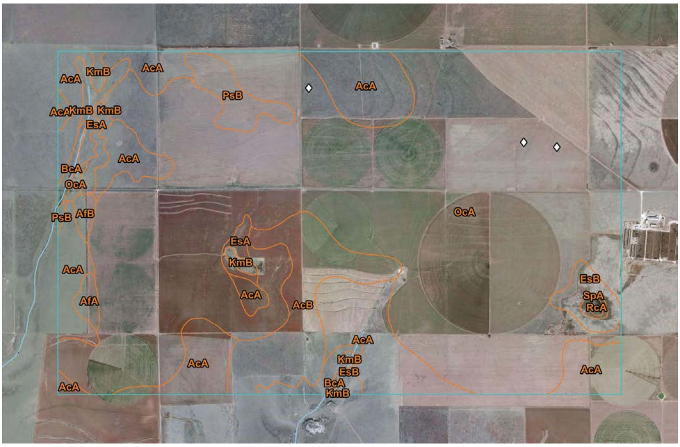
Soil Survey Maps and Map Products

Web Soil Survey (WSS) is the largest natural resource information delivery system in the world. It is the primary delivery mechanism for the maps and data of the National Cooperative Soil Survey and is operated by the USDA Natural Resources Conservation Service. Information can be displayed as maps (fig. A-2) or in tables. The user selects an area of interest on a map and then can view and print a soils map of the area. The user can also access additional soil data for the area. The mapping can be used for natural resource planning and management by landowners, townships, counties, and others. Some knowledge regarding soils data and map scale is necessary to avoid misunderstandings. WSS is updated and maintained as the single authoritative source of soil survey information.

The data system supporting WSS is the SSURGO (Soil Survey Geographic) database, which consists of spatial and tabular databases. SSURGO datasets consist of digital map data, tabular data, and information about how the maps and tables were created. The extent of a SSURGO dataset is a soil survey area, which may consist of a single county, multiple counties, or parts of multiple counties.

Soil maps generated in WSS show the soil map unit names and symbols. A legend of conventional and special symbols appearing on the soil maps (fig. A-3 and table A-3) is also generated. The maps are linked to information about the component soils and their properties for each map unit. Each map unit includes up to three major components and some minor components. Web Soil Survey allows map-based display and tabular data for: (1) soil properties and qualities, (2) interpretive ratings (suitabilities and limitations) for various uses, (3) soil reports, and (4) ecological site assessments.

Figure A-2



Soil map showing an area of interest on the Southern High Plains of western Texas and eastern New Mexico. The area is part of Major Land Resource Area 77C in Land Resource Area H. Note the distribution of map unit OcA (Olton clay loam, 0 to 1 percent slopes).

Figure A-3

MAP LEGEND

Area of Interest (AOI)
- Area of Interest (AOI)

Soils
- Soil Map Unit Polygons
- Soil Map Unit Lines
- Soil Map Unit Points

Special Point Features
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh or swamp
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other
- Special Line Features

Water Features
- Streams and Canals

Transportation
- Rails
- Interstate Highways
- US Routes

Background
- Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Curry County and Southwest Part of Quay County, New Mexico
Survey Area Data: Version 11, Sep 29, 2015

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Oct 9, 2010—Dec 31, 2010

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

The map legend and conventional symbols found on soil maps.

Table A-3

Map Unit Symbols and Names Displayed on the Soil Map for the Area of Interest

Curry County and Southwest Part of Quay County, New Mexico (NM669)			
Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
AcA	Acuff loam, 0 to 1 percent slopes	1,052.6	17.5%
AcB	Acuff loam, 1 to 3 percent slopes	373.9	6.2%
AfA	Amarillo fine sandy loam, 0 to 1 percent slopes	28.6	0.5%
AfB	Amarillo fine sandy loam, 1 to 3 percent slopes	23.6	0.4%
BcA	Bippus clay loam, 0 to 2 percent slopes, occasionally flooded	25.5	0.4%
EsA	Estacado loam, 0 to 1 percent slopes	86.0	1.4%
EsB	Estacado loam, 1 to 3 percent slopes	137.6	2.3%
KmB	Kimberson gravelly loam, 0 to 3 percent slopes	80.6	1.3%
OcA	Olton clay loam, 0 to 1 percent slopes	4,083.0	67.8%
PsB	Posey fine sandy loam, 1 to 3 percent slopes	113.4	1.9%
RcA	Ranco clay, 0 to 1 percent slopes, frequently ponded	5.6	0.1%
SpA	Sparenberg clay, 0 to 1 percent slopes, occasionally ponded	10.8	0.2%
Totals for Area of Interest		**6,021.1**	**100.0%**

Soil properties and qualities are presented as aggregate values or classes that were measured, observed, or estimated for each soil component of map units in the survey area. A broad array of physical and chemical properties, as well as soil qualities and features (such as depth, drainage class, and hydrologic soil group) are displayed on a thematic map and in tabular format.

Suitabilities and *limitations* are soil ratings for various uses, such as agricultural production, engineering, urban development, and waste and water management. Tables list the properties or qualities that limit a soil's suitability for given uses. The interpretations are displayed as thematic maps with a summary table for the soil map units in the selected area of interest.

For each map unit, a single value or rating is generated by aggregating the interpretive ratings of individual map unit components. This aggregation process is defined for each interpretation. Aggregation is the process by which a set of component values is reduced to a single value that represents the map unit as a whole. Once a single value for each map unit is derived, a thematic map for soil map units can be rendered. Aggregation is necessary because map units are delineated but individual components are not. For each component in a map unit, a corresponding percent composition is recorded. For example, a percent composition of 60 indicates that the corresponding component typically makes up approximately 60 percent of the map unit. Percent composition is a critical factor in some, but not all, aggregation methods. Table A-4 lists the various aggregation methods.

Soil reports include various formatted tabular and narrative reports (tables) containing data for each soil map unit in the selected area of interest and for each component of each soil map unit. The reports contain soil interpretive information as well as basic soil properties and qualities,

Table A-4

Aggregation Methods

[These methods determine the attribute value for thematic maps of soil properties and interpretative ratings in WSS.]

Method	Description
Dominant Condition	Groups components in a map unit based on like-values for the attribute. For each group, percent composition becomes the sum of the percent composition of all components in the group. These groups therefore represent conditions rather than components. If more than one group shares the highest percent composition, a corresponding tie-breaker rule determines which value is returned.
Dominant Component	Returns the attribute value associated with the component that has the highest percent composition in the map unit. If more than one component shares the highest percent composition, a corresponding tie-breaker rule determines which value is returned.
Most Limiting	Suitable only for attributes used to generate a soil suitablity rating for a particular use. The most limiting result among all components of the map unit is returned. This method may or may not represent the dominant condition. The result may be based on the limitations of a map unit component of minor extent.

Table A-4.—continued

Method	Description
Least Limiting	Suitable only for attributes used to generate a soil suitablity rating for a particular use. The least limiting result among all components of the map unit is returned. This method may or may not represent the dominant condition. The result may be based on the limitations of a map unit component of minor extent.
Weighted Average	Computes a weighted average of the value for all components in the map unit. Percent composition is the weighting factor.
All Components	Returns the lowest or highest attribute value among all components of the map unit, depending on the corresponding tie-breaker rule. In this case, the tie-breaker rule indicates whether the lowest or highest value among all components is returned. For this aggregation method, percent composition ties cannot occur. The result returned represents either the minimum or the maximum value of the corresponding attribute throughout the map unit. The result may be based on a map unit component of minor extent.
Absence/ Presence	Returns a value, for all components of a map unit, that indicates if a condition is always present, never present, or partially present or whether the condition's presence or absence is unknown.
No Aggregation Necessary	Although the majority of soil attributes are associated with a component of a map unit, some are associated with a map unit as a whole. An attribute of a map unit does not have to be aggregated in order to render a corresponding thematic map. Therefore, the "aggregation method" for any attribute of a map unit is referred to as No Aggregation Necessary.
Component Percent Cutoff	Components whose percent composition is below the cutoff value are not considered. If no cutoff value is specified, all components in the database are considered.
Tie-Break Rule	Indicates which value should be selected from a set of multiple candidate values, or which value should be selected in the event of a percent composition tie.

Table A-4.—continued	
Method	**Description**
Interpret Nulls as Zero	Indicates if a null value for a component should be converted to zero before aggregation. This conversion is done only for map units that have at least one component for which the attribute value is not null.
Layer Options	For an attribute of a soil horizon, a fixed depth range must be specified. Either centimeters or inches may be used, but the bottom depth must be greater than the top depth. The top depth can be greater than zero. When "Surface Layer" is specified, only the surface layer or horizon is used to derive a value for a component. When "All Layers" is specified, all layers recorded for a component are considered when deriving the value for that component. Whenever more than one layer or horizon is considered, a weighted average value is returned based upon layer or horizon thickness.
Month Range	For an attribute that is recorded by month, a range of months must be specified.

but do not require aggregation of data. Soil reports are organized by category, such as "Recreational Development." A description of each report (table) is available.

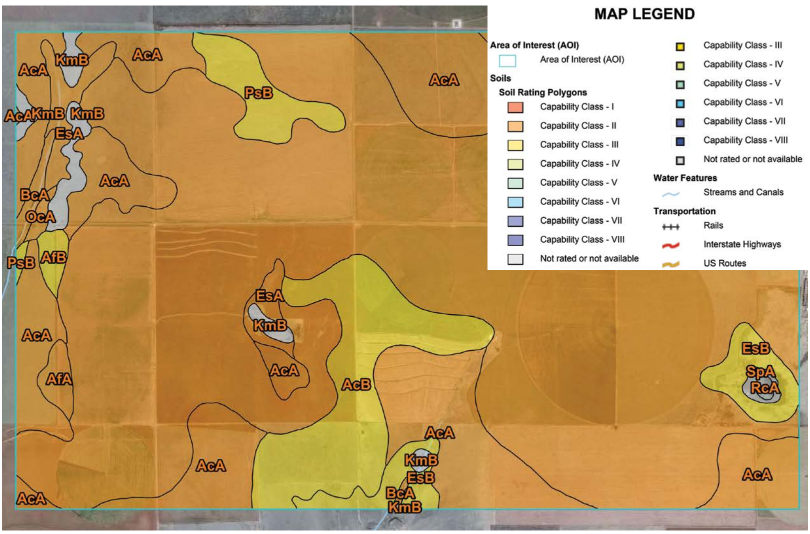
Examples of Maps and Reports

The following pages demonstrate a few of the many maps that can be generated in Web Soil Survey with the full integration of spatial and tabular databases. Over 100 thematic maps for various suitability or limitation ratings have been developed as well as almost 50 thematic maps of soil properties and qualities. Each thematic map includes a tabular report by map unit and component for the thematic data. In addition, over 60 tabular reports of various combinations of soil interpretations, properties, and features can be generated.

Land Capability Class

Land capability classification shows, in a general way, the suitability of soils for most kinds of field crops (fig. A-4). Crops that require special management are excluded. The soils are grouped according to their limitations for field crops, the risk of damage if they are used for crops, and the way they respond to management. The criteria used in grouping the soils do not include major and generally expensive landforming that would change slope, depth, or other characteristics of the soils, nor do they include possible but unlikely major reclamation projects. Capability classification is not a substitute for interpretations that show suitability and limitations of groups of soils for rangeland, for woodland, or for engineering purposes.

Figure A-4



Map showing land capability class.

Capability classes, the broadest groups, are designated by the numbers 1 through 8. The numbers indicate progressively greater limitations and narrower choices for practical use. The classes are defined as follows:

Class 1 soils have few limitations that restrict their use.

Class 2 soils have moderate limitations that reduce the choice of plants or that require moderate conservation practices.

Class 3 soils have severe limitations that reduce the choice of plants or that require special conservation practices, or both.

Class 4 soils have very severe limitations that reduce the choice of plants or that require very careful management, or both.

Class 5 soils are subject to little or no erosion but have other limitations, impractical to remove, that restrict their use mainly to pasture, rangeland, forestland, or wildlife habitat.

Class 6 soils have severe limitations that make them generally unsuitable for cultivation and that restrict their use mainly to pasture, rangeland, forestland, or wildlife habitat.

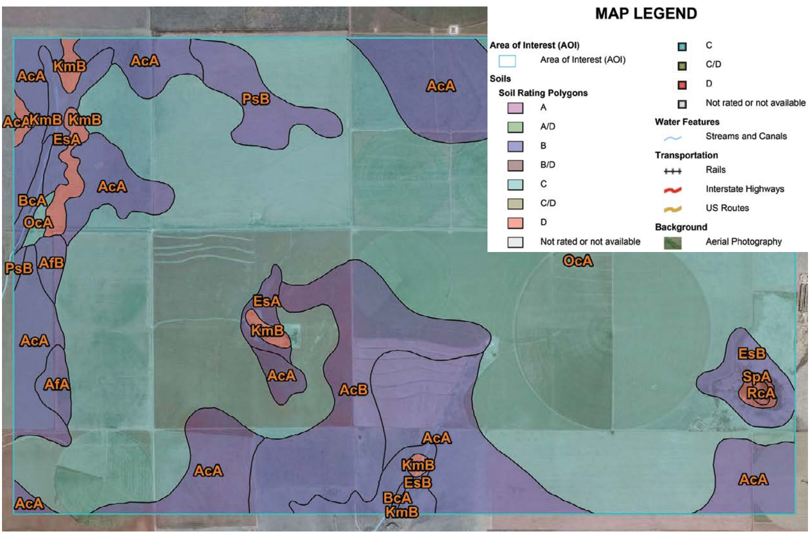
Class 7 soils have very severe limitations that make them unsuitable for cultivation and that restrict their use mainly to grazing, forestland, or wildlife habitat.

Class 8 soils and miscellaneous areas have limitations that preclude commercial plant production and that restrict their use to recreational purposes, wildlife habitat, watershed, or esthetic purposes.

Hydrologic Soil Group

Hydrologic soil groups are based on estimates of runoff potential (fig. A-5). Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long duration storms. The soils in the United States are assigned to four groups (A, B, C, and D)

Figure A-5



Map showing hydrologic soil groups. Soils in group A are most permeable and soils in group D least permeable. Dual classes (e.g., C/D) indicate hydrological soil groups for both the drained and undrained conditions.

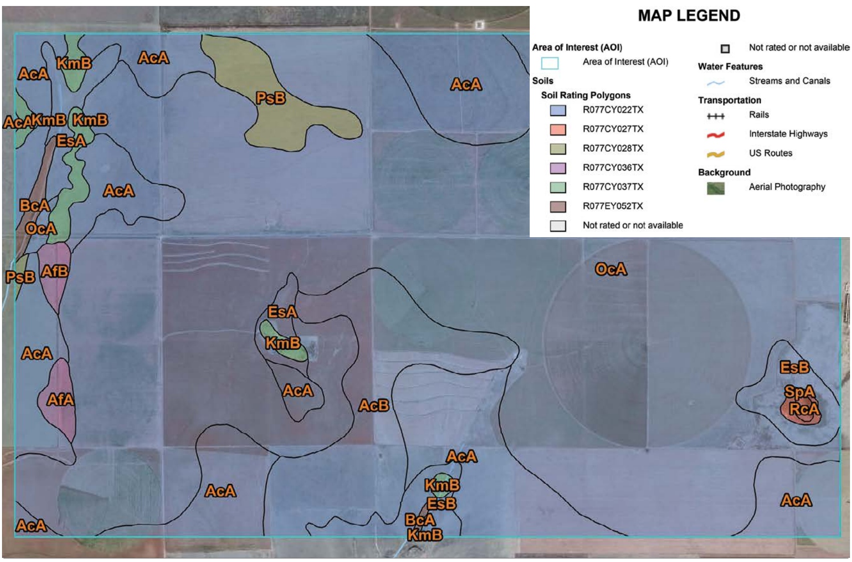
and three dual classes (A/D, B/D, and C/D) where the first letter is for drained areas and the second is for undrained areas. Only the soils that are in group D in their natural condition are assigned dual classes.

Ecological Site Assessments

Ecological site assessments document the ecological conditions and plant communities correlated to components of the soil map units. They provide maps (fig. A-6), descriptions, tables, illustrations, and photographs (fig. A-7). They include information on species composition, annual production, and growth curves and a state-and-transition diagram (fig. A-8).

An ecological site is the product of all the environmental factors responsible for its development. It has characteristic soils that have developed over time; a characteristic hydrology, particularly infiltration and runoff, that has developed over time; and a characteristic plant community (kind and amount of vegetation). The vegetation, soils, and hydrology are all interrelated. Each is influenced by the others and influences the development of the others. For example, the hydrology of the site is influenced by development of the soil and plant community.

Figure A-6



Map showing ecological sites. The dominant ecological site is Deep Hardland, 16-21" PZ (R077CY022TX).

Figure A-7

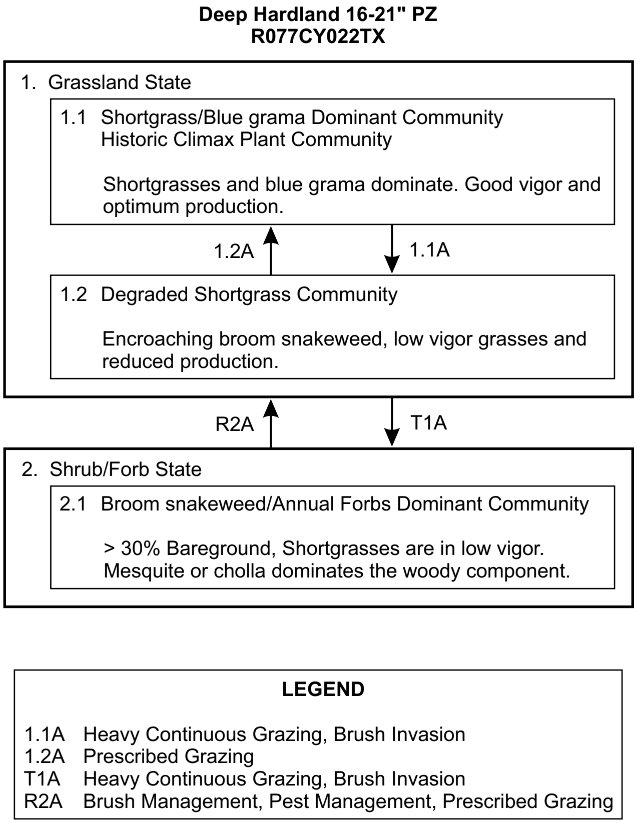
Shortgrass/blue gramma dominant community of the Deep Hardland ecological site (R077CY022TX).

The plant community on an ecological site is typified by an association of species that differs from that of other ecological sites in the kind and/or proportion of species or in total production.

An ecological site name provides a general description of a particular ecological site. For example, “Loamy Upland” is the name of a rangeland ecological site. An ecological site ID is the symbol assigned to a particular ecological site.

The “Dominant Ecological Site” map identifies the dominant ecological site for each map unit, aggregated by dominant condition. Other ecological sites may occur within each map unit. Each map unit typically consists of one or more components (soils and/or miscellaneous areas). Each soil component is associated with an ecological site. Miscellaneous areas, such as Rock outcrop, Sand dunes, and Badlands, have little or no soil material and support little or no vegetation. These areas are not linked to an ecological site. The table “Ecological Sites by Map Unit Component” lists all of the ecological sites for each map unit component in the area of interest.

Figure A-8



State-and-transition model showing pathways and causes of change in the plant communities.

Engineering Properties

Table A-5 gives the engineering classifications and the range of engineering properties for the layers of each soil in the survey area. Included are hydrologic soil group, USDA texture, Unified and AASHTO classification, coarse fragments, percent of soil passing standard sieves, liquid limit, and plasticity index.

Soil Chemical Properties

Table A-6 shows estimates of some chemical characteristics and features that affect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

Table A-5

Engineering Properties and Classifications

Map unit symbol and soil name	Pct. of map unit	Hydro-logic group	Depth	USDA texture	Classification		Pct Fragments		Percentage passing sieve number—				Liquid limit	Plasticity index
					Unified	AASHTO	>10 inches	3-10 inches	4	10	40	200		
			In				*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*
AcA—Acuff loam, 0 to 1 percent slopes														
Acuff	85	B	0-12	Loam	CL, CL-ML	A-4, A-6	0- 0-0	0- 0-0	100-100-100	100-100-100	90-99-100	51-60-68	24-35-39	6-13-19
			12-38	Clay loam, sandy clay loam, loam	CL	A-6, A-7-6	0- 0-0	0- 0-0	100-100-100	100-100-100	91-98-100	55-63-67	31-40-45	13-19-22
			38-58	Clay loam, sandy clay loam	CL, SM	A-6, A-7-6	0- 0-0	0- 0-0	90-93-97	80-87-95	73-85-95	45-54-67	27-35-45	5-14-24
			58-80	Clay loam, sandy clay loam, loam	CL, SC	A-6, A-7-6	0- 0-0	0- 0-0	93-96-99	86-91-98	78-89-98	45-55-69	27-37-48	8-17-27
AcB—Acuff loam, 1 to 3 percent slopes														
Acuff	85	B	0-12	Loam	CL	A-6, A-4, A-7-6	0- 0-0	0- 0-0	100-100-100	100-100-100	90-98-100	60-67-74	27-36-43	8-13-19
			12-38	Clay loam, sandy clay loam, loam	CL	A-6, A-7-6	0- 0-0	0- 0-0	100-100-100	100-100-100	91-98-100	55-63-67	31-40-45	13-19-22
			38-58	Clay loam, sandy clay loam	CL, SM	A-6, A-4, A-7-6	0- 0-0	0- 0-0	90-93-97	80-87-95	73-85-95	45-54-67	27-35-45	5-14-24
			58-80	Clay loam, sandy clay loam, loam	CL, SC	A-6, A-4, A-7-6	0- 0-0	0- 0-0	93-96-99	86-91-98	78-89-98	45-55-69	27-37-48	8-17-27

Table A-6

Soil Chemical Properties

Map symbol and soil name	Depth	Cation-exchange capacity	Effective cation-exchange capacity	Soil reaction	Calcium carbonate	Gypsum	Salinity	Sodium adsorption ratio
	In	*meq/100g*	*meq/100g*	*pH*	*Pct*	*Pct*	*mmhos/cm*	
AcA—Acuff loam, 0 to 1 percent slopes								
Acuff	0-12	9.0-23	—	6.6-7.8	0	0	0.0-2.0	0-1
	12-38	16-25	—	6.6-8.4	0-2	0	0.0-2.0	0
	38-58	8.4-11	—	7.9-9.0	40-65	0	0.0-2.0	0-1
	58-80	14-20	—	7.9-8.4	15-70	0	0.0-2.0	0-1
AcB—Acuff loam, 1 to 3 percent slopes								
Acuff	0-12	11-23	—	6.6-7.8	0	0	0.0-2.0	0-1
	12-38	16-25	—	6.6-8.4	0-2	0	0.0-2.0	0-1
	38-58	8.4-11	—	7.9-9.0	40-65	0	0.0-2.0	0-1
	58-80	14-20	—	7.9-8.4	15-50	0	0.0-2.0	0-1
AfA—Amarillo fine sandy loam, 0 to 1 percent slopes								
Amarillo	0-10	8.6-17	—	6.6-8.4	0	0	0.0-2.0	0-1
	10-41	16-27	—	7.4-8.4	0-3	0	0.0-2.0	0-1
	41-56	9.6-13	—	7.9-9.0	40-65	0	0.0-2.0	0-1
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