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Site and Landscape Characterization for Ecological Studies

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There is growing awareness of the importance of adequately defining the environment when conducting ecological studies. Our objective in this chapter is to present the rationale and procedures for describing soils and landscapes (sites) for such studies. We use the term *site characterization* to refer to the entire suite of soil biogeophysical descriptors that places a site into an environmental context. A primary goal of any environmental study is to understand a phenomenon or set of linked phenomena, whether attributes or processes. Macro- and microclimate, soil, and landscape properties influence both ecosystem attributes and processes. To understand our own data or those of others, we must understand the environment in which they were collected. In addition, we are increasingly called upon to apply our research results to land management issues. Extrapolation from study sites can be either statistically rigorous or qualitative. Both understanding and extrapolation demand good site characterization.

The importance of soil and landform for affecting and defining the environment has been directly and indirectly assessed, and an understanding of the landscape can clarify ecological relationships. The strong influence of slope and aspect on the productivity of sites for forest growth has been universally recognized (Carmean 1975), and the greater lushness and productivity of cove forests compared with ridgetops (Whittaker 1956) is an ecological axiom. Standing stocks of nitrogen, phosphorus, and carbon vary dramatically but not monotonically along a topographic sequence of sites in arctic Alaska (Giblin et al. 1991). McAuliffe (1994) clearly demonstrated that previous assumptions of a simple gradient model of vegetation across *bajadas* of Arizona was incorrect. A mosaic of distinct landscape patches related to landform age and erosional history affect vegetation patterns and ecosystem processes. Under the gradient assumption, this mosaic is considered to be statistical noise. In fact, knowledge of the causes and consequences of the mosaic leads to insights about the system. Many environmental measurements and soil and landscape features are related and therefore predictable (Hall and Olson 1991), providing strong justification for their characterization.

Site descriptions must consider the spatial and temporal dimensions of ecological studies. Spatial descriptions should define the extent, scale, and specific location of the study. *Spatial extent* refers to the size of the study area, *scale* refers to the minimum size of a spatial feature that is considered or can be represented, and *location* refers to the geographic coordinates of the study area or of specific sampling points. The hierarchical levels of organization for the components of the soil-landscape system can be described by distinct scales (Fig. 2.1). Each scale requires a different set of descriptors and defines a different set of processes. The temporal dimension refers to the frequency of observations that are made at a specific site. For example, some sites may be visited only once to collect data, whereas other sites may be visited repeatedly for intensive study. If a site is visited only once, then the required site description is likely to be less detailed than that for a site undergoing intensive study.

Because the level of detail required either for an individual study or for comparison across sites varies with the property being measured and its spatial and temporal scales, we recognize here three levels of intensity of site description and soil sampling (see also Chapter 1, this volume). At the first level, the primary interest is in properties or processes of the surface soil, and description and sampling may be carried out by personnel who are relatively inexperienced in soil science. At the second level, more detailed information is collected following standard procedures (Soil Survey Division Staff 1993); work is usually carried out by advanced graduate students or experienced field scientists. At the third level, detailed descriptions are made and samples collected by scientists trained in soil pedogenesis.

When is a site adequately characterized? Is there a raison d'être for site characterization, or is data collection simply a rote procedure to ensure that all possible questions are addressed? In our view, the rationale for site characterization is to describe the biophysical soil environment of the site as the basis for a wide range of ecological investigations, but especially with respect to its suitability for organisms. The four operationally defined environmental factors of light, nutrients, heat, and water provide a focus for our discussion.

Site characterization helps to describe the environment for light and for the entire spectrum of solar radiation. Location affects photoperiod and is quantified by latitude and longitude or by other georeferencing systems. Topographic setting may also affect the environment for light through the differential shading of solar radiation. Characterization of the environment for nutrients is complex, and many facets will be discussed elsewhere in this volume, but routine soil characterization includes measurement of a suite of nutrient-related properties. Heat, or the instantaneous measure of temperature, is clearly affected by location. Slope inclination and aspect as they affect incoming solar radiation, simple elevation above a datum, and the possibility of air drainage in response to temperature gradients all affect the thermal regime of a site.

Specifying the operational environment with respect to water provides a further focus for site characterization. Location and elevation define the macroclimate of a

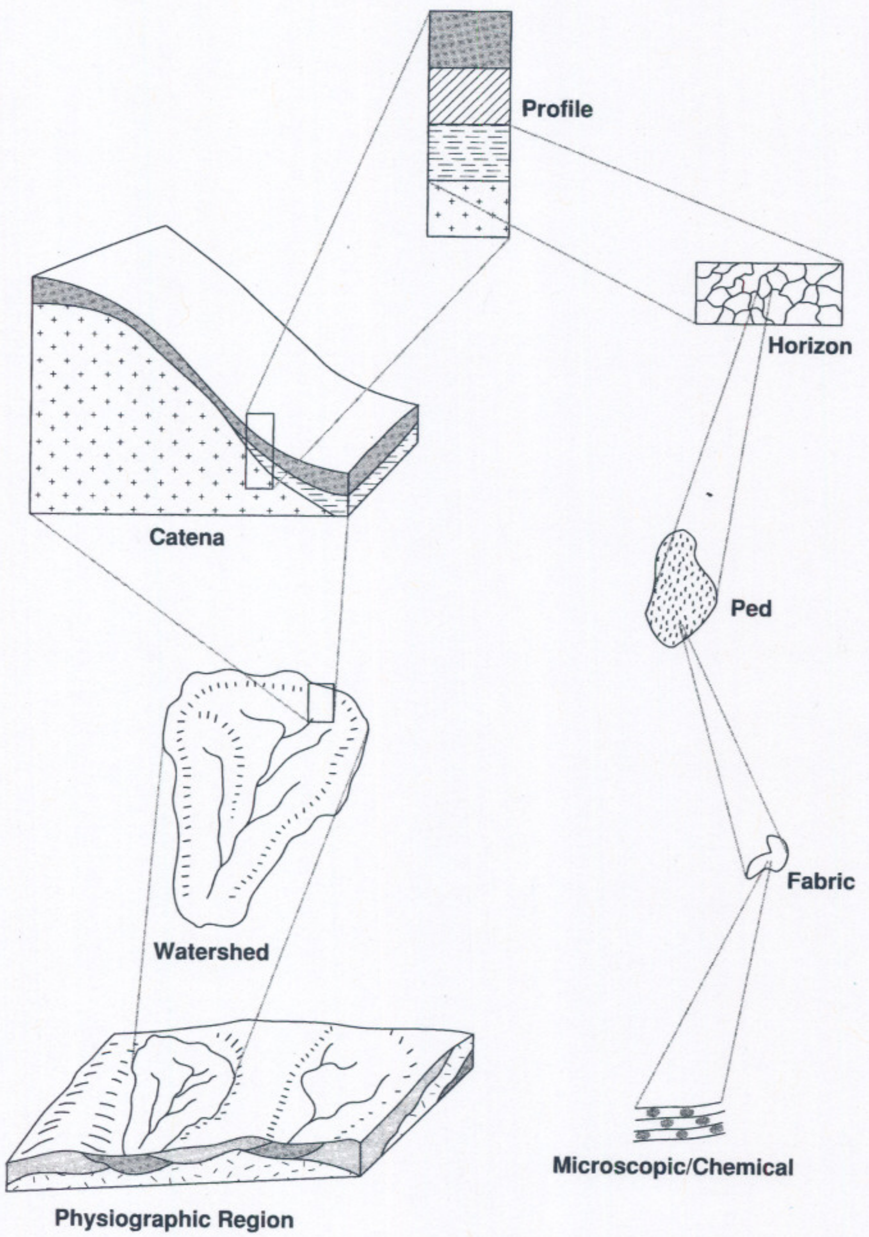

Figure 2.1. Hierarchical levels of organization of the soil-landscape system.

site and profoundly affect its water regime. Within similar macroclimatic zones, this regime is also affected by the surface and subsurface flow paths of water through the system. Is the site steeply sloping or nearly horizontal? Is it underlain by an impermeable soil or rock stratum? Is it seasonally impermeable? Is there an indication of redoximorphic features (mottles) in the soil? At what depth? Is there a local, seasonally defined water table? At what depth is the regional water table? Is evapotranspiration from the site affected by slope and aspect? What is the texture and the water-holding capacity of the soil—both by layer or horizon and summed over all layers? In summary, a good site characterization should provide at least a qualitative description of the environment with respect to light, nutrients, heat, and water, providing a unifying basis and rationale for the characterization.

Structural Organization of Soil Landscapes

Soil-landscape systems are inherently spatial phenomena, and any description of their characteristics is made within the context of spatial scale. A complex mosaic of processes occurs at several spatial scales within the soil-landscape system. Jenny (1941) defined the factors that influence the development of soils in landscapes as

$$s = f(cl, o, r, p, t, \ldots)$$

where

s = a soil property
cl = climate
o = organisms representing the combined effect of both fauna and flora
r = topographic relief
p = the soil parent material or geologic substrate
t = time or relative soil age
. . . = other site-specific factors such as human disturbance

From a simplistic view, these factors define an equilibrium state toward which soil characteristics adjust through time, the underlying assumption being that a unique soil will develop for that equilibrium state. In reality, these factors continually change, and the soil never reaches an equilibrium. Nonetheless, this framework is a useful conceptual model for understanding the environmental factors that influence both past and present ecosystem processes.

Recognizing that the factors influencing soil development operate at a range of spatial scales, we can define a hierarchy that describes the organization of the soil-landscape system (Fig. 2.1). Site characterization requires a description of the soil-landscape system at these multiple scales, and we will use this multiscale model as a framework for describing site characterization. The interaction of biophysical processes occurring from regional to microscopic scales determines the environment of the entire terrestrial ecosystem.

The physiographic region and landform (Fig. 2.1) can be described in broad terms from existing information concerning soils, landscapes, climate, and vegetation. Watersheds provide a means for further subdividing physiographic regions into spatial units linked by hydrologic processes. Repeating soil patterns within watersheds can often be described by catenas. Considerable information at the level of the soil catena complex (Fig. 2.1) can be determined from knowledge of general soil stratigraphy and the configuration of the topographic surface. The spatial organization of soil components at this level is closely related to the age of the surface and to water and particle movement through the soil, with the accumulation of particles in the upper 1–2 meters of the profile. The profile, horizon, and ped levels of organization (Fig. 2.1) are described at specific points in the landscape by standard methods.

While information concerning the fabric and microscopic/chemical levels of organization (Fig. 2.1) can be gleaned from field observations, laboratory analyses are usually required for comprehensive physical, chemical, and mineralogical analysis. We will divide our discussion of this multiscale soil-landscape system into three general categories: (1) we will focus on the physical geography of study sites at the physiographic region, landform, and watershed/catena levels of organization; (2) we will use soil morphology at specific points in the landscape to describe the profile, horizon, and ped levels of organization; and (3) we will refer to soil laboratory analyses to characterize the structural organization of soils at the fabric and microscopic/chemical levels.

Physical Geography

Physiographic Region/Landform

At a broad level of generalization, land masses having similar physical structure have been classified into *physiographic regions* that divide the earth into unique sets of landforms and geologic substrate(s) that have been and are being influenced by similar geomorphic and/or geologic processes, climate, and vegetation. Physiographic regions usually cover large areas, such as the Ridge and Valley Physiographic Province of the eastern United States, extending from Pennsylvania to northern Georgia. While the composition of soil parent material may vary within physiographic regions, the geologic processes responsible for its occurrence at a site are usually similar. Hence, physiographic regions are often delineated by commonality in bedrock lithology, regional landforms, or the depositional environment for transported soil parent materials (glacial tills, outwash, loess). Landforms further divide physiographic regions into more homogeneous subunits. In the Ridge and Valley Province, for example, two obvious landforms are ridges and valleys, but those landforms can be further subdivided.

There are numerous classification systems that consider physiographic regions, each with a different emphasis depending on the purpose of the classification. Such systems include ecoregions (Bailey and Cushwa 1981), major land resource areas (Austin 1972), and physiographic provinces (Fenneman 1928). Physiographic regions are typically delineated on maps at scales of 1:100,000 to 1:1,000,000. Major land resource areas, with national coverage at map scale of 1:10,000,000, provide the basis for defining working regions for the National Cooperative Soil Survey.

Although the emphasis in characterizing a site is on properties at the surface, lithology of the underlying bedrock may also be important. Although in some cases the bedrock is well below the weathered soil horizons, knowledge of bedrock lithology may help one to understand the chemistry and the mineralogy of the surface materials and even the evolution of the landform that is being studied. The history of land use and vegetation change is also important information. The presence of a plow layer—a clearly delineated, constant-depth surface zone of organic-rich mineral soil—indicates former cultivation, as does the presence of stone fences or stone piles. Old fields in the local area also indicate the potential for past agricultural activities at the study site. The successional status of the vegetation may also provide clues to disturbances that have affected the site and the soil-related processes therein such as nitrogen mineralization. For example, processes in a primary successional sequence following flooding, glacial recession, or volcanic activity may be associated with much different soil characteristics than those associated with secondary succession, such as following logging, intense grazing, agriculture, or fire.

The characteristics of a site can also be more fully understood by historical information on a much longer time scale. Paleosols, pollen diagrams, isotope ratios, and other indicators of past environments help place the current site and environment in a temporal context. Landform evolution, soil development, and vegetation composition are linked to past climatic history.

A complete description of the physiographic region and landform of a site should include:

- physiographic classifications of interest (ecoregion, physiographic province, major land resource area);
- major landform (mountains, till plain, basin and range, etc.);
- predominant soil parent material type (residuum, alluvium, glacial drift, loess, colluvium, lacustrine deposit, etc.);
- lithology of the predominant soil parent material (sandstone, shale, limestone, granite, gneiss, etc.);
- approximate age of the geomorphic surfaces;
- geomorphic history;
- predominant vegetation communities (tallgrass prairie, boreal forest, oak savanna, etc.);
- 30-year average annual and monthly climate data, including precipitation and maximum and minimum temperatures;
- freezing depth;
- evapotranspiration potential;
- other physiographic features;
- land-use history; and
- location.

Most of this information can be obtained from existing broad-scale inventories. County-level (2nd order; Soil Survey Division Staff 1993) soil surveys also contain information on the range of soil parent materials, the geomorphic history of an area, and summaries of local climatic data.

Watershed/Soil Catenas

Watersheds are logical subdivisions of physiographic regions that define portions of the landscape linked by hydrologic processes. The hierarchical arrangement of watersheds with respect to stream order provides a method for defining soil and landscape variability at spatial scales intermediate to physiographic regions and hillslope catenas. Where hydrologic processes are a major factor influencing soil formation and subsequent variability within physiographic regions, watersheds are appropriate spatial units to further partition variability. In many cases, however, topographically based watershed boundaries are superimposed over a complex mosaic of soil variability attributable to differences in other soil-forming factors such as parent material and microclimate. As such, watersheds may not always be ideal spatial units to subdivide soil and landscape variability because not all pedogenic, geomorphic, and/or geologic processes occur within the confines of watershed delineations. Eolian (wind) erosion and transport, for example, often transcends watershed boundaries.

Soil variability within watersheds may be further subdivided according to repeating patterns of soil variability occurring along hillslopes. These repeating patterns are described as soil catenas and are often linked to topographic variability. Milne (1935) first described a *catena* as a "chain" of soils hanging between two summits. A catena can be viewed as a hydrologically-linked segment of the landscape. Soil variability along hillslopes is usually related to two factors: (1) changes in soil parent material resulting from geologic or geomorphic processes, and (2) alterations of the soil by hillslope-scale hydrologic, biotic, and biogeochemical processes. Geologic materials often differ in resistance to erosion. As a result, the higher elevations on erosional landscapes are usually composed of resistant materials, and lower elevations are composed of more-erodible materials that may be covered by a mantle of depositional sediment (colluvium or alluvium). Hillslope relationships can be very complex in landscapes where multiple geomorphic and pedogenic cycles have occurred. Soil parent materials on hillslopes may range from homogeneous to very heterogeneous depending on the history of the site.

Superimposed onto this variability in parent material are alterations of the soil mantle due to past and contemporary hydrologic and geomorphic processes. Soil water on hillslopes may follow one or several pathways:

- surface runoff;
- lateral flow in shallow soil horizons above relatively impermeable subsoils;
- vertical flow through the soil profile;
- some combination of the above two flow paths; and
- return to the atmosphere via evapotranspiration.

The precise pathway of water flow depends on the shape of the land surface, surface stratigraphy, the quantities, timing, and frequency of precipitation, and the potential for evapotranspiration. In humid climates the magnitude, direction, frequency, and timing of water movement are primary factors affecting differential soil development on hillslopes and the associated presence of different biological communities. These pathways of water movement in the upper few meters of soil are responsible for migration of soil particles and solutes from uplands to lower hillslope positions. This inextricable linkage of soils and landscapes by hydrologic and geomorphic processes is often ignored, leading to such environmental problems as accelerated soil erosion, constriction or elimination of wetlands, and soil salinization. The imprint of these hydrologic processes can often be found in the morphologic characteristics of soils, and the pathways of movement can often be inferred by an analysis of terrain attributes.

While the catena concept describes soil variability along hillslopes, differences among soils within a landscape can also be related to specific landforms. In many cases these landforms are the result of specific geomorphic processes that redistribute soils and soil parent material by transport and deposition via wind or water. These processes are often episodic, and the current arrangement of soil materials may have been manifested over very long periods by processes that may or may not be active today. Changes in radial patterns of soil texture along the surface of alluvial fans are examples of deposition. Soil variability in sequences of stream terraces formed in response to variations in sea level is an example of erosional processes.

Information on soil catenas and other soil patterns can be found in soil survey reports. The composition of soil map units is defined by soil taxonomic units (usually soil series). Three kinds of soil map units are used: (1) soil associations define areas where two or more soil types follow discernible patterns across the landscape, (2) soil complexes define areas where the pattern of two or more soil types is random or not distinguishable at the mapping scale, and (3) soil consociations are map units that primarily contain a single soil type. Modern reports usually have a series of block diagrams that depict the topographic relationships of the predominant soils in the major landforms of the survey area (e.g., Calus 1996). If a soil survey is not available for the immediate area of interest, surveys of adjacent areas may have similar landform and soil relationships. While soil surveys can provide valuable background information, they are *not* intended for site-specific application. On-site investigations are absolutely necessary to adequately document soil and site conditions for ecological investigations. This requires both a description of the topographic surface and of soil profiles located along a hillslope catena or in other soil patterns.

Terrain Attributes

Attributes of the topographic surface can be either measured or estimated from visual inspection. Local terrain attributes describe the shape and orientation of a small segment or patch of the landscape, and regional attributes consider the patch relative to the overall hillslope and/or catchment. A fundamental set of terrain attributes (slope gradient, aspect direction, plan and profile curvature, and catchment area) define the shape and orientation of the topographic surface in geometric space and the convergence or divergence of water flow and other pedogenic influences.

Local Terrain Attributes

Local terrain attributes refer to the shape and orientation of the land surface within a patch, often called a "window." The window may be on the order of 100–1000 m^2 in highly variable landscapes and 1000–10,000+ m^2 in less variable landscapes. Slope gradient, slope curvature, and aspect direction are local terrain attributes that would be similar within an appropriately sized window. Similarly, a window would occur exclusively on a single hillslope position.

Mathematically, slope gradient is the first derivative of elevation measured in a specific direction. Although the direction is usually that of maximum descent, other directions such as perpendicular to maximum descent may be useful in complex terrain. Slope gradient plays a major role in determining the potential rate of water movement over and within the soil. Soil materials and water are likely to be transported downslope from steeper to lower slope gradients. Slope gradient can be measured in the field using simple hand-held instruments such as clinometers or Abney levels. More precise measurements can be made with stationary surveying devices, but this level of precision is seldom justified in ecological studies. When measuring slope, care should be taken to avoid including a break or change in slope within the distance necessary for the measuring instrument.

The distance over which the slope gradient and other local terrain attributes are measured should always be recorded, and is a function of both topographic variability and expected use of the data. The frequency of variation in the topographic surface varies considerably among landscapes. For example, consider slope gradients in two distinctly different terrains, one a highly undulating glacial moraine landscape and the other a major mountain range. Neglecting microrelief (differences of <1 meter), measured slope gradients from the top of a hillslope to distances of 10, 100, and 1000 m in the glacial landscape would probably all be different. However, measured gradients at equivalent distances from the top of a major ridge in the Appalachian Mountains would probably all be similar. The scale of variation within the local landscape must therefore be considered.

Slope curvature is the rate of change in slope gradient, and mathematically is the second derivative of elevation. It is quantitatively expressed in units of distance per distance squared (m/m^2). Slope curvature is also a directional attribute, usually measured both along the axis of maximum descent (profile curvature) and perpendicular to that direction (plan curvature). In the field, slope curvature is usually described qualitatively by the change in slope gradient from the local window into adjacent windows:

- *concave,* in which the slope gradient decreases in direction of measurement;
- *straight,* in which the slope gradient remains constant in direction of measurement; and
- *convex,* in which the slope gradient increases in direction of measurement.

Based on these three curvature classes, nine possible combinations of plan and profile curvature can be defined. Slope curvature affects the relative dispersion or accumulation of water in the landscape. As a broad generality, convex slopes are water spreading (divergent flow), straight slopes are water transporting (parallel flow), and concave slopes are water accumulating (convergent flow). Water and sediment tend to accumulate in zones of convergent flow and are removed from zones of divergent flow, affecting soil characteristics. Soils in concave areas (convergent flow) often have accumulations of sediment, organic matter, and redoximorphic features indicating prolonged periods of saturation and biochemical reduction. Soils on convex slopes (divergent) often are eroded, with consequently lower levels of organic matter and plant nutrients. Although field descriptions of slope curvature are usually qualitative, quantitative measurements can be calculated from digital elevation models using techniques of digital terrain analysis (Moore et al. 1993).

Aspect refers to the compass direction of the vector describing the direction of maximum slope gradient. In the field, aspect is determined as a compass bearing in the direction that the hillslope is facing (the compass is pointed away from the hillslope). If magnetic declination is appreciable, correction for the deviation between true and magnetic north must be made. For long and/or steep slopes, aspect determines the incident solar radiation and can dramatically influence soil water and the type of vegetation. Simulation models can be used in conjunction with digital elevation models to derive and map estimates of incident solar radiation across the landscape (Moore et al. 1991). Because incident radiation is also affected by other factors, including latitude, shading by adjacent hillslopes, and cloud cover, these models require considerable parameterization to obtain actual as opposed to relative estimates. Shading by adjacent landforms is especially important at higher latitudes.

Regional Terrain Attributes

While hydrologic and geomorphic processes are influenced by the shape and orientation of the immediate landscape, they are also influenced by the location of the window in the larger landscape. The use of the term *regional* in this context refers to a larger region surrounding the local terrain window, usually the entire hillslope or basin. The primary attribute affecting hydrologic and geomorphic processes at this scale is the potential rate and quantity of water that can enter the window from upslope, either over the soil surface as run-on or through the soil as lateral interflow. To assess the potential influence of these processes, information on both soil stratigraphy and landform configuration is needed. In general, highly stratified or low-permeability soils will be more strongly affected by these processes than unstratified, highly permeable soils. Two general approaches can be used to assess the influence of the regional terrain—landscape position descriptions and catchment area measurements.

The regional setting of a local landscape window can be qualitatively described by the hillslope position; these positions have been defined in the profile direction (Fig. 2.2). Cross-sectional hillslope positions can be more completely described by combinations of the slope gradient, profile curvature, and catchment area (Tab. 2.1). These positions are relatively easy to recognize on simple idealized hillslopes. Landscapes are often complex, however, with variation in the topographic surface occurring at several different spatial scales so that local hillslopes may be nested within a larger hillslope complex. In these situations the hillslope position of a spe-

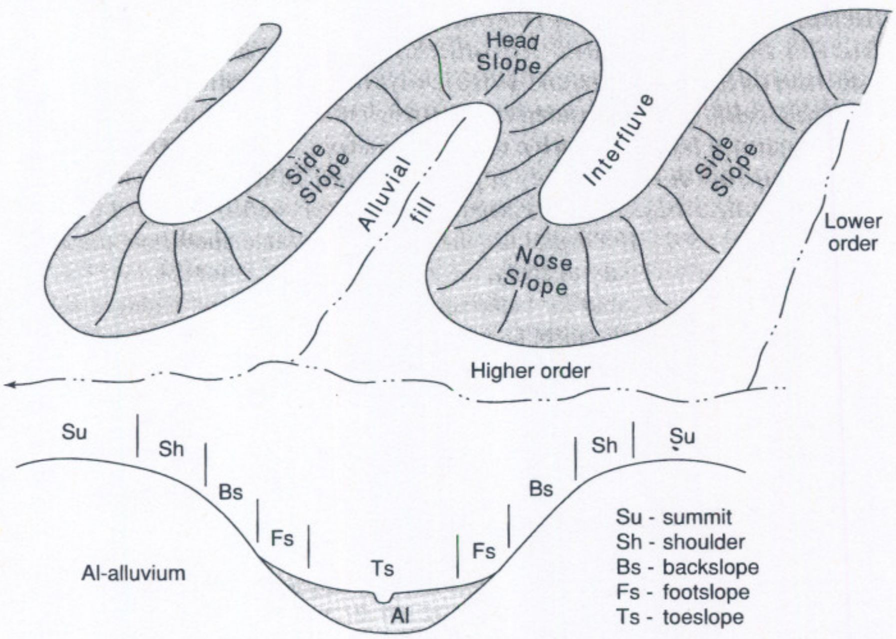

Figure 2.2. The components of an incised valley (above) and of a hillslope profile (below). Modified from Ruhe and Walker (1968).

cific point on the landscape can be described in terms of both the major and minor hillslope components. For example, a site may be located both on the sideslope of a major hillslope component and on the toeslope of a minor hillslope component. The cross-sectional hillslope position describes the convergence or divergence of hillslope processes along only one axis (downslope profile direction). To accurately portray hillslope morphology, a qualitative description of hillslope characteristics in the plan direction (perpendicular to profile) is also necessary. This requires description of slope positions along the contour of the slope; divergent slope positions are interfluves and noseslopes, convergent positions are headslopes and drainageways, and parallel slopes are backslopes (Fig. 2.2).

Table 2.1. General Description of Cross-Sectional Hillslope Positions in Terms of Slope Gradient, Profile Curvature, and Catchment Area

Hillslope Position	Slope Gradiant	Profile Curvature	Catchment Area
Summit	Low	Straight	Lowest
Shoulder	Moderate	Convex	Low
Sideslope	Steep	Straight	Moderate
Footslope	Moderate	Concave	Moderate
Toeslope	Low	Concave	High
Depression/Drainageway	Low	Concave	Highest

The regional terrain can be alternatively and more quantitatively described by catchment area measurements. These measurements determine the upslope watershed area that contributes flow to a particular point in the landscape. Drainage divides have no catchment area, and drainageways or depressions have relatively large catchment areas. Direct measurement of catchment area is difficult in the field but can be estimated from topographic maps. Calculations of catchment area for an entire landscape can be carried out by applying flow-tracing algorithms to a digital terrain model (digitized contours, triangular irregular networks, or digital elevation models; Moore 1992). If a digital terrain model is available, most flow-tracing algorithms are relatively easy to apply, are able to compensate for spurious "pits" in the data, and are applicable for landscapes with both open and deranged surface drainage. Estimates of catchment area are especially useful for defining spatial patterns of soils in landscapes with appreciable lateral flow (Moore et al. 1993; Bell et al. 1994). The vertical proximity of a point on the landscape to the nearest expression of the local free water surface (lake, stream, wetland, etc.) appears to be a useful terrain attribute to explain patterns of soil in landscapes without appreciable lateral flow. Vertical proximity can be estimated in the field, from topographic maps, or calculated from digital terrain models using simple algorithms (Bell et al. 1992).

Soil Morphology

The characteristics of the soil at specific points in the landscape are the focus of the next level of soil-landscape organization. The extrapolation of soil characteristics from specific points to the three-dimensional landscape requires an understanding of the spatial relationships between soil and landscape characteristics. The techniques used by professional soil scientists to create soil maps by spatial extrapolation (Holmgren 1988) combine art and science, and their discussion is beyond the scope of this chapter. Our objective here is to discuss techniques for describing soil characteristics at specific points in the landscape.

The art of describing a vertical exposure of soil, the soil profile, has been standardized over time. The color, texture, structure, and other soil attributes that are included in descriptions can all be interpreted to provide information far beyond their simple tabulation. Even those who are not experts in such interpretation can produce meaningful data much as a patient describes his or her symptoms in lay terms and a skilled physician arrives at a diagnosis. Another point, and one that often confuses the neophyte, is that horizon designators as identified by letters and numbers (e.g., A, Bk2) are interpretations from horizon descriptors. These designators are not absolutely necessary if the description itself is accurate. In fact, an inappropriate designator may more seriously impair communication than would a modest error in a description. The bottom line, therefore, is that although horizon designations are very helpful, their absence does not detract from a good description. A third point is that a description of a soil profile is simply an attempt to separate the vertical section into layers so that there is greater homogeneity within than between layers. Most soils are less isotropic vertically than horizontally, so that a vertical separation reduces variance in measured attributes. The essence of the recognition of a soil layer (= horizon) is therefore a change in one or more properties. Each vertical change has the potential to define a new layer. As in many other activities, those who describe soil profiles can be roughly divided into splitters and lumpers. Some are not satisfied unless they have detected and described every nuance of change, while others require a much higher threshold of change in order to consider it sufficiently different to describe.

Some soil properties that are included in a profile description have not been traditionally emphasized in soil science because of the field's agronomic tradition and bias. For example, the organic surface of many uncultivated soils (e.g., the forest floor) is very different from surface residues from an agronomic crop. Similarly, most land used for agronomy has minimal stones—stony land is simply not suitable for most crops. For ecological studies, a good description of organic horizons and of stone volume and characteristics is very important.

Morphological Description

Standard methods used to describe soil morphology encompass the profile, horizon, and fabric levels of soil organization (Fig. 2.1). The soil profile can be exposed by hand probes or augers, mechanical probes or augers, or soil pits excavated by hand or backhoe. Hand augers or push probes extract disturbed or undisturbed cores of soil whose depth depends on both the length of the auger or probe and the perseverance of the operator. The variety of augers (such as open and closed bucket, Dutch auger, McCauley peat auger, etc.) is designed to accommodate a wide range of soil conditions. Hand methods are the only option in areas where access roads do not exist or where mechanical equipment cannot be used. Because soil cores can be extracted rather quickly, hand augers and probes permit the examination of soil morphological characteristics at many points in the landscape. The disadvantage of their use, however, is that the sample is usually relatively small (a few centimeters in diameter), restricting observation of soil horizonation and structure. Disturbance by the auger or probe may also obscure certain soil morphological characteristics. At sites accessible by vehicle, mechanical augers or probes mounted on trucks or trailers and powered by hydraulic drives allow more rapid coring to deeper soil depths. However, the disturbance of cores remains a problem. A soil profile is best exposed by digging a pit, usually to a depth of approximately 2 meters. Although pits via backhoe are ideal, accessibility and cost can be limiting. The depth to which soils are described depends on the objectives of the study, but a reasonable approach is to describe soils in detail to 100 cm by excavation of a pit, and then to use a bucket auger for the further description of materials to an additional 100 cm depth.

An important consideration when excavating a soil pit is the sun angle. The side of the pit to be described should face the sun to ensure optimal lighting for observation. After the pit is excavated, the pit face must be prepared for description by shaving off the outer few centimeters of soil with a tiling spade or mason's trowel, beginning at the top of the pit and working toward the bottom. This removes artifacts in the pit face created by smearing during the excavation, a common problem with backhoe buckets. After the pit face has been prepared, a portion (usually 0.5–1 m in width) should be "picked," not cut or scraped, using a hand tool such as a blunt knife or trowel. Begin at the top of the pit and work toward the bottom to keep the picked face clean. The goal of this exercise is to break the soil along natural planes of weakness to reveal soil structure. Comparisons can also be made of soil color differences on the ped surfaces (picked surface) and the ped interiors (shaved surface).

After the pit face has been prepared, the best technique is to stand a few meters back from the pit face and observe and delineate the major horizons. Closer examination of changes in soil characteristics can then be used to delineate additional horizons. The specific terminology and methodology for delineating horizons within a soil profile and for describing the morphological characteristics (depth ranges, color, structure, consistence, texture, reaction, and horizon boundary characteristics) are described in the *Soil Survey Manual* (Soil Survey Division Staff 1993) and will not be repeated here. Terminology used to designate master and subhorizons for description and diagnostic horizons for classification is also described in the *Soil Survey Manual* (Soil Survey Division Staff 1993) and in the *Keys to Soils Taxonomy* (Soil Survey Staff 1996). The latter is frequently updated to reflect changes in taxonomy used by the USDA–Natural Resources Conservation Service. Examples of profile descriptions are included in the Appendix of this chapter.

The forest floor in forests and organic litter layers in other ecosystems should be described if present. If appropriate, the type and proportion of rock fragments on the soil surface should also be described. Traditionally in soil science, the measurement point of reference for description was the top of the mineral soil, with organic horizons lying above that zero-point and mineral horizons below. One of the reasons for this standard was that the organic horizon may be ephemeral, either seasonally or with change in flora or fauna. In many cases, for example, by midsummer earthworms have totally consumed all litter material from the previous autumn. In other cases, changes in plant communities may markedly alter the thickness and/or composition of the forest floor. In the most recent recommendation for soil descriptions, however, the soil surface is considered the top of the part of the organic horizon that is at least slightly decomposed (Soil Survey Division Staff 1993). The forest floor is usually described by both color and stage of decomposition, the alteration from the original state of the organic material. The Oi, Oe, and Oa horizons (Soil Survey Division Staff 1993) are approximately equivalent to the L, F, and H layers, respectively (Pritchett and Fisher 1987), and differ in the degree of original plant fiber that they contain. In some cases, separation of the forest floor from the mineral soil material is difficult, with a diffuse gradation between the two. In other cases, changes are abrupt, and the mineral and organic layers can be easily separated. There is no hard rule for this separation. Another important characteristic of the soil surface that should be described in forests is coarse woody debris (see Chapter 11, this volume).

Many soil chemical (e.g., sorption and desorption of metals and organic compounds, exchange processes, weathering reactions, nutrient availability, buffering capacity) and physical (e.g., bulk density, shrink-swell properties, aeration, infiltration, and hydraulic conductivity) processes and properties depend on the nature and relative quantities of the mineral and organic components of the soil (Dixon and Weed 1989). Differences in mineralogy can affect many ecological processes (Sollins et al. 1988). For most medium- to fine-textured soils, the majority of soil chemical properties are determined by mineralogy of clays because of their higher specific surface and charge compared to silts and sands. Relative quantities of carbonates, gypsum, and other more soluble salts are also important because they are much more reactive than the common silicate minerals. Quantitative assessment of the mineralogical components of soils, particularly the clay mineralogy, is a highly technical task, but qualitative to semiquantitative measurements are routinely made in many private and public laboratories, including those of university departments of soil science and geology.

Accurate and precise descriptions of soil profiles can be achieved only with both a basic understanding of pedological concepts and field experience with local soils and landscapes. Because there is an element of subjectivity in describing soil profiles, consistency is vital. Achieving this consistency requires experience, and novices are likely to encounter difficulties without some initial guidance from experienced soil scientists in the local area. If the study site has high value in terms of research, either because of the investment of significant resources or because of the long-term nature of the observations or monitoring, direct field assistance by an expert in soil science is essential. As explained, the separation of soil horizons is part description and part interpretation. Experience with the soils in an area is essential for meaningful interpretation. In addition, some soil properties that are determined in the field, such as texture and consistence, require training and practice with calibration to laboratory data to ensure reproducibility and accuracy. In fact, if the collected data are used to classify the soils, a perspective to be kept in mind is that "no classification is better than a bad classification."

Materials

Materials usually required for soil morphological descriptions include the following:

1. Munsell soil-color book
2. Blunt knife or other implement to pick the soil
3. Tiling spade and geologist hammer
4. Field pH test kit
5. 1 *N* HCl to test for presence of carbonates
6. α,α'-dipridyl to test for presence of ferrous Fe
7. Measuring tape
8. Nails to mark horizon boundaries
9. Field notebook with standardized profile description forms
10. Reference information on terminology for soil profile description
11. Spray-type water bottle
12. Hatchet or clippers for cutting vegetation and roots
13. A hand lens to examine soil fabric
14. Heavy plastic bags to return samples to the laboratory

Field Location

Precise location of field sites is important for site inventory, for repeated visits to the same site, or for spatial analysis using geographic information systems. Global Positioning Systems (GPS) provide a highly accurate and potentially cost-effective means of obtaining locations for a large number of field sites. Accurate positioning is now possible worldwide by nearly continuous coverage of GPS satellites. A variety of hand-held GPS receivers are available. GPS uses a constellation of 24 navigational satellites that have been placed in precise earth orbits by the U.S. military. Low-energy signals (pseudorandom code) are broadcast from synchronized atomic clocks in each satellite, and the distance to the satellites is calculated by comparing time differences between transmission and reception of the signals by the ground receiver, which also contains a synchronized clock. Precise positions are calculated by considering the distance to multiple satellites. Positional errors can be minimized by using two ground-based receivers, one at a known location (base station) and the second at the target. The adjustment of the target position by the error detected at the base station is known as *differential correction* or *differential GPS* (DGPS). Base stations and targets must usually be within 450 km of one another. Differential correction can be made in real time by receiving telemetry from base stations or after data collection using postprocessing techniques. Many hand-held units provide 1–5 m accuracy for a specified portion (usually 65% or 95%) of the observations. For submeter accuracy, DGPS receivers with special features are required. Use of inexpensive, hand-held receivers without differential correction can result in significant positional errors.

Laboratory Analyses

Although site characterization is a field exercise, independent of laboratory operations, some soil properties that are routinely described require laboratory measurement. These measurements are essential for characterizing intensive sites and usually are predicted or inferred for less-intensive sites. Routinely determined properties for soil characterization include particle-size distribution (texture), pH, organic C, exchangeable bases, cation exchange capacity, and bulk density. In many cases, water retention characteristics are also measured, but since they covary with organic C and particle size they can usually be predicted from those properties.

The objective in measuring a soil property is most often to precisely estimate its mean. Because most soil properties are not normally distributed but are more nearly lognormally distributed, this objective requires careful scrutiny. If the properties are lognormally distributed, many fewer samples are usually required to achieve similar precision of their estimated mean than if normality is assumed (Grigal et al. 1991). A second point is that as analytical and statistical procedures have become more refined, our ability to measure precisely in the laboratory and to differentiate statistically among similar observations or treatments has increased. As a result, the perception of meaningful variation and differences in ecosystems has become unrealistic. Because cost must be considered in any assessment of laboratory measurement, less precise but inexpensive laboratory procedures may result in greater overall precision than highly precise but expensive procedures. Greater relative costs of laboratory procedures, compared with field sampling, may lead to increasing the number of field composites and performing fewer laboratory analyses (Mroz and Reed 1991).

Both soil sampling and laboratory procedures are described in detail in other chapters in this volume and will not be further considered here.

Pedotransfer Functions

Extrapolation of ecological information to regional scales requires integration of large data sets collected by different investigators. To standardize data sets, it is useful to fill in data gaps where analyses were not conducted or sample collection was not possible. Although direct measurements are preferred, some studies that require large data sets and hence sample collection and analyses are not practical. Data collected by the National Cooperative Soil Survey and by individual investigators have led to the development of functional relationships among soil properties; these can provide some insight into the interrelationships among soil biological, physical, and mineralogical components. These functional relationships that relate different soil characteristics to one another have been termed pedotransfer functions (Bouma 1989).

Water Retention

A variety of pedotransfer functions have been developed that relate other soil properties to water retention (Rawls et al. 1991). Particle size distribution, organic matter, and bulk density are soil properties that commonly have been used to describe water retention (Rawls et al. 1991).

A synthesis of relationships for surface soils in the literature (Shaykewich and Zwarich 1968; Gupta and Larson 1979; Rawls et al. 1982; De Jong et al. 1983; Rawls et al. 1983) yields

$$P_{33}(\mathrm{cm^3/cm^3}) = 10^{-3} \times [4.12 \times \text{clay}\ (\%) + 22.09 \times \text{organic matter}\ (\%) - 1.22 \times \text{sand}\ (\%) + 174.8 \times \text{bulk density}\ (\mathrm{g/cm^3})],\ S_{y.x} = 0.004\ \mathrm{cm^3/cm^3},$$

and

$$P_{1.5}(\mathrm{cm^3/cm^3}) = 10^{-3} \times [4.06 \times \text{clay}\ (\%) + 10.37 \times \text{organic matter}\ (\%) - 0.33 \times \text{sand}\ (\%) + 41.3 \times \text{bulk density}\ (\mathrm{g/cm^3})],\ S_{y.x} = 0.002\ \mathrm{cm^3/cm^3},$$

where

P_{33} = water retention at 33 kPa (1/3 bar),
P_{15} = retention at 1.5 MPa (15 bar)

Available water is often defined as the difference between these values.

Bulk Density

Soil bulk density is an indirect measure of the relative volume of solids and voids in a soil; hence it provides an indication of the soil's ability to store and transport water and gases, as well as an estimate of soil strength. Bulk density (*BD*) is also critically important for determining the mass balance of elements and water within ecosystems. The bulk density of most surface soils is closely related to soil organic matter, and this relationship has been explored and verified many times by pedotransfer functions. A synthesis of relationships in the literature (Curtis and Post 1964; Jeffrey 1970; Adams 1973; Alexander 1980; Grigal et al. 1989) yields

$$BD\ (\mathrm{g/cm^3}) = \mathrm{EXP}[0.23 - 0.037 \times \text{organic matter } (\%)],\ S_{y.x} = 0.05\ \mathrm{g/cm^3}.$$

Other pedotransfer functions have been developed to estimate operationally defined clay content, where standard laboratory procedures developed by midlatitude soil scientists are deficient, and to estimate a suite of soil chemical properties such as cation exchange capacity, base saturation, and pH.

Extrapolation

Classic statistical procedures assume that variation in measured properties is randomly distributed among sample units. In contrast, variation in measured properties in a field setting often is related to the distance between sample locations. In this chapter we have emphasized the predictable variation in soil properties with differences in landform position, soil parent material, soil age, and many other factors. In addition to the expected or predictable variation in soil properties, another part of the variation cannot be attributed to known causes and is therefore termed *random* or *chance variation.* The essence of geostatistical methods is the exploration of the spatial component of variation, and its quantification and subsequent use in estimating properties at unsampled locations. Geostatistical methods were first developed by D. G. Krige for determining the spatial extent of mineral deposits, but since then the techniques have been applied in a wide range of field studies (Warrick et al. 1986; Ver Hoef and Cressie 1993; Robertson et al. 1997).

Geostatistical procedures basically quantify changes with distance in either correlation or covariation of measurements of the same property. In an ideal case, variation increases with distance from a small constant (the nugget) to an asymptotic maximum (the sill). In other words, the nugget is a random component of variation that is unrelated to distance, while the sill is the variation at a distance beyond which measurements are independent of one another. The results of the analysis are used to make unbiased optimal interpolated estimates of properties at unsampled locations (i.e., *kriging;* Trangmar et al. 1985). The results of such interpolations are often presented as maps of properties such as soil organic matter (e.g., Crawford and Hergert 1997). A two-stage analysis can also be conducted, where preliminary data are collected via transect or other scheme, and geostatistics are used to help optimize both intensity and location of a refined sampling scheme.

One of the key concepts in geostatistics is isotropic versus anisotropic variation. Isotropic variation occurs where properties vary in the same way in all directions, so that variation among samples is simply a function of distance. In contrast, variation in most soil properties also has a directional component (e.g., downslope). Where variation among samples has components of both direction and distance, it is termed *anisotropic*. Although analyses are somewhat more complicated in the latter case, recognition of anisotropy is important in using geostatistics in soil science (Crawford and Hergert 1997). As with any sophisticated statistical technique, a rich literature has developed regarding the uses of geostatistics in field studies (see Trangmar et al. 1985; Warrick et al. 1986; ver Hoef and Cressie 1993).

Level of Intensity

The level of detail required for a site characterization varies with the objectives of a specific study, and we therefore recognize three levels of intensity. These range from Level 1, with primary interest in the surface soil and description and sampling by personnel who are relatively inexperienced in soil science, to Level 3, with detailed descriptions by those trained in soil pedogenesis.

At Level 1 intensity, and at the spatial scale of the physiographic region and landform, a detailed site description would not be performed. A general description of a site will be sufficient, and if a soil survey of the area is available it should be used to identify the soil map unit. Each sampling spot should be characterized with respect to position on slope (summit to depression) and slope gradient, slope curvature, and aspect direction. Position on the microrelief should also be noted. If a GPS is used to determine sampling locations, differential correction is probably not necessary. Soil sampling will usually be by sample tube, auger, or tiling spade, but no pit would be dug. Soil morphology would be described only by noting the presence of sharp and obvious changes in soil characteristics within the sampling depth. Although soil mineralogy would not be determined in detail, the carbonate content, using the descriptions of effervescence from the *Soil Survey Manual* (Soil Survey Division Staff 1993) can be estimated.

Both the second and third levels of intensity require similar information that may differ only in the detail and the expertise with which it is collected. A complete description of the physiographic region and landform should be made. The location of each sampling point should be determined using a GPS with differential correction. A complete field description of the shape and orientation of the topographic surface can be achieved by descriptions of local terrain attributes within a local window, coupled with descriptions of hillslope position in both the cross-sectional (downslope profile) and contour (plan) directions. The only field equipment required is a compass, an instrument for measuring slope gradient (Abney level, clinometer, etc.), and a careful eye to discern landscape positions. Descriptions of hillslope position should involve walking across and viewing the hillslope from several different vantage points to minimize bias. If more quantitative information is needed and if a digital terrain model is available, a complete quantitative description of the topographic surface can be achieved by using digital terrain analysis to calculate the fundamental attributes of slope gradient, aspect direction, plan and profile curvature, and catchment area.

In both Levels 2 and 3, detailed descriptions of soil morphology should be made. Soil pits are usually excavated, and complete descriptions are carried out following standard procedures (Soil Survey Division Staff 1993). In the case of Level 2, the recommended description should extend to 100 cm; for Level 3 it should extend to 200 cm. In the case of Level 2, horizons may not be formally designated, and the taxonomic placement of the soil would not be determined. For Level 3, both of these details would be included.

For medium- to fine-textured mineral soils, a qualitative or semiquantitative assessment of clay mineralogy is the most important mineralogical parameter. For soils potentially affected by volcanic tephra deposition, clay mineralogical analyses are considerably more difficult than the standard X-ray diffraction analyses due to the low degree of crystallinity of secondary mineral species. In many cases, chemical and physical measurements can be used to infer clay mineralogy. For coarse-textured mineral soils, the relative amount of weatherable minerals (e.g., feldspars, pyroxenes, amphiboles, micas) compared with quartz can be determined by grain counts based on optical microscopy in thin section.

Conclusions

Descriptions of sites, encompassing descriptions of the landscape and associated soils, must consider the spatial and temporal dimensions of ecological interest. Several distinct scales describe hierarchical levels of organization for the components of the soil-landscape system (Fig. 2.1). Each scale requires a different set of descriptors and elucidates a different set of processes. A good site characterization should provide at least a qualitative description of the environment of a site with respect to light, nutrients, heat, and water, including its movement, providing a unifying theme and rationale for characterization. In addition, such a description should provide the basis for understanding a phenomenon or set of linked phenomena, either attributes or processes. Finally, a good site description should provide a firm basis to move research results from study sites to other areas via interpolation and/or extrapolation for both science and land management objectives.

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Appendix: Examples of Soil Profile Descriptions

Sartell Pedon—Mixed, Frigid, Typic Udipsamment

Location: Cedar Creek Natural History Area, Anoka and Isanti Counties, Minnesota. The following is a description of a representative pedon of the Sartell series on a 1.5% nearly plane slope in an old field at an elevation of 280 m, located 502 m west and 597 m north of the southeast corner of Sec. 22, T. 34 N., R. 23 W. (Colors are for moist soils unless otherwise noted.)

- Ap—0–18 cm; dark brown (10YR 3/3) sand; weak, fine and medium, subangular blocky structure; loose; common very fine and fine roots; abrupt, smooth boundary.
- B—18–71 cm; dark yellowish brown (10YR 4/4) fine sand; massive breaking to single grain; loose; few, dark brown (7.5YR 5/4) fillings; few fine roots; gradual, smooth boundary.
- C1—71–107 cm; very pale brown (10YR 7/4), fine sand; single grain; loose; gradual, smooth boundary.
- C2—107–152 cm; light yellowish brown (10YR 6/4) sand; single grain; loose; one reddish brown (5YR 4/4), 1–2 mm thick, irregular, weakly cemented band occurs at about 127 cm; gradual, smooth boundary.
- C3—152–178 cm; very pale brown (10YR 7/4) sand; single grain; loose; one reddish brown (5YR 4/4), 2–3 mm thick, irregular, weakly cemented band occurs at about 152 cm.
- C4—178–254 cm; very pale brown (10YR 7/4) fine sand; single grain; loose.

Parnell Pedon—Fine, Smectitic, Frigid, Typic Argiaquoll

Location: Near Dalton, in Otter Tail County, Minnesota. The following is a description of a representative pedon of the poorly drained Parnell series at the toeslope of a south- to west-facing hillslope. Location is NE 1/4 of SE 1/4, Sec. 10, T. 131 N., R. 42 W. (Colors are for moist soil unless otherwise noted.)

- Ap—0–14 cm; black (2.5Y 2.5/1) loam; weak, fine subangular blocky structure; friable; many coarse and medium roots; no effervescent reaction; clear, smooth boundary.
- A1—14–44 cm; black (2.5Y 2.5/1) silt loam; moderate fine subangular blocky structure; friable; many fine and very fine roots; no effervescent reaction; gradual smooth boundary.
- A2—44–67 cm; black (10YR 2/1) loam with few (<2%) fine prominent dark yellowish brown (10YR 3/4) mottles; moderate coarse and medium subangular blocky structure; friable few fine and very fine roots; no effervescent reaction; gradual smooth boundary.
- Btg1—67–88 cm; very dark gray (10YR 3/1) silty clay loam; moderate medium and fine subangular blocky structure; friable; discontinuous prominent dark gray (10YR 4/1) clay films on faces of peds and in pores; many (>20%) fine prominent reddish brown (5YR 5/4) oxidized rhizospheres; few fine and very fine roots; no effervescent reaction; gradual wavy boundary.
- Btg2—88–102 cm; 55% very dark gray (10YR 3/1) and 40% dark gray (10YR 4/1) clay loam with many (>20%) fine faint dark grayish brown (10YR 4/2) mottles; moderate medium and fine subangular blocky structure; friable; many (>20%) fine prominent reddish brown (5YR 5/4) oxidized rhizospheres; few very fine roots; strong effervescent reaction; clear, abrupt boundary.[1]
- Bkg1—102–115 cm; grayish brown (2.5Y 5/2) clay loam with many (>20%)

fine faint light brownish gray (10YR 6/2) and common (2–20%) medium prominent olive brown (2.5Y 4/4) mottles; strong medium subangular blocky structure; friable; discontinuous black (10YR 2/1) coats in root channels and pores; few very fine roots; strong effervescent reaction; gradual wavy boundary.

- Bkg2—115–145 cm; grayish brown (2.5Y 5/2) loam with many (>20%) fine prominent strong brown (7.5YR 4/6) mottles; strong medium subangular blocky structure; friable; many (>20%) fine prominent gray (10YR 6/1) carbonate threads; few very fine roots; strong effervescent reaction; gradual smooth boundary.
- Bkg3—145–180 cm; grayish brown (2.5Y 5/2) loam with many (>20%) fine prominent strong brown (7.5YR 4/6) and many (>20%) fine prominent gray (10YR 6/1) mottles; strong medium subangular blocky structure; friable; few (<2%) fine prominent black (10YR 2/1) iron-manganese concentrations; no roots; strong effervescent reaction.[2]

Appendix Notes

1. stone line present between Btg2- and Bkg1-horizon in bottom of Btg2-horizon; siliceous and carbonate pebble-sized stones.

2. Bkg3-horizon extends down to 220 cm, where there is a color change to light olive brown (2.5Y 5/3) with grayish brown (2.5Y 5/2) mottles; this may be the C-horizon (texture is loam or clay loam).

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STANDARD SOIL METHODS

FOR

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