Chapter 3
Soils



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3.1 Introduction

Soils are dynamic, natural bodies that serve as the foundation of most terrestrial ecosystems (Whalen and Sampedro 2010; Binkley and Fisher 2019). Soils play a crucial role in ecosystem function, serving as a non-renewable source of mineral nutrients and organic matter in addition to being the growth medium for vegetation (Urbanska et al. 1997). Consequently, considering soil information during restoration planning efforts has been shown to improve the success of ecological restoration activities (Callaham et al. 2008; Heneghan et al. 2008; Stanturf et al. 2021).

Recent research in the red spruce (*Picea rubens*) forests of the central Appalachians demonstrates the importance and value of incorporating soils information into restoration planning. These investigations showed that current soil properties can be used to determine if a site was historically dominated by red spruce forests (Nauman et al. 2015a). High-elevation red spruce and spruce-fir ecosystems in the southern Appalachians share many similarities with red spruce ecosystems of the central Appalachians (land use history, climate, topography), but less research on the links between soil properties and site history has been conducted in the southern Appalachians (Wolfe 1967; Busing 1985; Lietzke and McGuire 1987; Feldman 1989; Feldman et al. 1991a, b). This chapter begins with a discussion of some of the

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basic properties of soils and the ecosystem services they support before examining the notable characteristics of soils that underlie red spruce forests in central and southern Appalachia. The chapter concludes with a discussion of the impacts of past management on red spruce soils and the critical ways that soils inform and direct the restoration of red spruce ecosystems.

3.2 Soils 101

Given the importance of soil properties and functions to red spruce ecosystems, it is beneficial to begin with an introduction to soils. Soils are the unconsolidated material on the immediate surface of the Earth that serve as a medium for plant growth. The role of soils in sustaining ecosystem functions derives from soils being a dynamic mixture of organic and mineral materials, water (with its associated dissolved components), and various gases. Importantly, soils also provide habitat to a biologically diverse collection of organisms, ranging from bacteria and fungi to macroinvertebrates and small mammals.

The soil properties we observe and measure are a result of complex and ongoing interactions among climate, organisms (plants, animals, fungi, bacteria, etc.), topography, and parent material (bedrock or other sediments) over time (Dokuchaev 1899; Jenny 1941). Climate influences many factors of soil development, driving processes like weathering rates, leaching, and biotic influences (Binkley and Fisher 2019). At any given location, the development of soil properties is influenced by the topography, chemical and physical characteristics of the parent material, ecological disturbances, and land use history (Binkley and Fisher 2019).

The interconnected nature of these soil forming factors results in a great deal of variability in soil properties across even short distances. Soil scientists characterize differences in soil properties in a variety of ways (Soil Survey Staff 2024), and ultimately use that information to classify soils using the U.S. system of Soil Taxonomy (Soil Survey Staff 1999). For a detailed description of soil profiles and soil horizons, see Sidebar 3.1. For a discussion of soil classification, see Sidebar 3.2.

Sidebar 3.1 Soil Profiles and Soil Horizonation Soil properties change with depth below the soil surface. Many soils develop distinct layers that have formed in place within the soil profile. These soil horizons differ chemically, physically, or biologically from the layers above and below. To soil scientists, the soil horizons are the context for interpreting the stories a soil has to tell about the environmental conditions that influenced the formation of the soil over thousands of years, the effects of more recent land use and management practices, and the future potential for land use and management practices. The types and sequence of horizons at a given site are also used to classify the soil (see Sidebar 3.2).

When investigating soils, the observed soil horizons are given alphanumeric labels as shorthand names that reflect their dominant properties (e.g., color, texture, structure). At a minimum, each horizon is labeled with a capital letter that designates the master horizon. There are six master soil horizons commonly used to name the naturally occurring layers within the soil in central and southern Appalachia (see Table 3.1 and Fig. 3.1). Additional properties of each master horizon are often denoted by adding lowercase letters that serve as subordinate distinctions to the master horizons (see Table 3.1 for subordinate distinctions common to red spruce ecosystems). The resulting names for soil horizons (e.g., Ap, Bhs, Bt, Cr) help communicate the key properties of soil horizons. Other conventions for labeling soil horizons include the use of transitional horizons share the properties of two adjacent master horizons (e.g., AB, EB). Numbers can be added as prefixes to indicate changes in parent materials within the soil profile (e.g., 2Bw) or as suffixes to indicate a sequence of horizons with the same letter designations (e.g., Bs1-Bs2-Bs3).

Of particular importance in the red spruce (*Picea rubens*) ecosystem are organic horizons (O, Oi, Oe, Oa) and spodic horizons (Bs, Bh, Bhs). O horizons may have one of three subordinate distinctions to indicate the degree of decomposition of the organic soil materials in the horizon, with Oi horizons the least decomposed, Oa the most decomposed, and Oe representing intermediate levels of decomposition. Spodic horizons are often darker and/or redder in color than adjacent horizons and exhibit smeary consistence due to the poorly crystalline organically-bound Fe and Al minerals that have accumulated through the podzolization process (Soil Survey Staff 1999, 2024). In soils with well-expressed spodic materials, an E horizon usually separates the O horizons from the spodic materials. For more information on horizon nomenclature, refer to the Keys to Soil Taxonomy (Soil Survey Staff 2022, p 377–384), the Field Book for Describing and Sampling Soils (Soil Survey Staff 2024), or a soil science textbook.

Table 3.1 Soil master horizons and commonly associated subordinate distinctions in the central and southern Appalachians (Soil Survey Staff 2022)

Master horizon	Description	Subordinate distinctions commonly used with each master horizon
O	Comprised of organic material from dead plant and animal residues that generally accumulates at the surface above the mineral soil	i. Slightly decomposed e. Intermediate decomposition a. Highly decomposed
A	Topmost mineral horizon that generally contains enough partially decomposed organic matter to give the soil a darker color than the horizons below it	p. Indicates disturbance by tillage, pasturing, or similar agricultural activities
E	Layer dominated by leaching and/or the eluviation of clay particles, organic matter, and/or iron and aluminum oxides, resulting in a gray or white layer dominated by sand and silt sized particles	
B	Layer that forms below O, A and/or E horizons that has undergone soil development such that the original structure of the parent material (bedrock) is no longer discernable	h. Indicates an illuvial accumulation of organic matter evidenced by a smeary consistence and dark soil colors s. Indicates illuvial Fe and Al oxides evidenced by soil colors that are redder or more orange than adjacent layers w. Indicates a distinct color or structure change from horizons above or below without clay accumulation t. Indicates the accumulation of clay that has weathered in the horizon or been translocated to the horizon through leaching and illuviation g. Indicates the layer is saturated with water, which results in gray (low chroma) colors from reduced forms of iron x. Indicates a fragipan or fragic properties evidenced by firm and brittle consistence; increased soil densities of this layer may impede water flow or root penetration
C	Layer that forms below the A, E and/or B horizons that has not been sufficiently altered by soil genesis to qualify as a B horizon	r. Indicates weathered, soft, or diggable bedrock
R	Hard consolidated bedrock with little evidence of weathering	

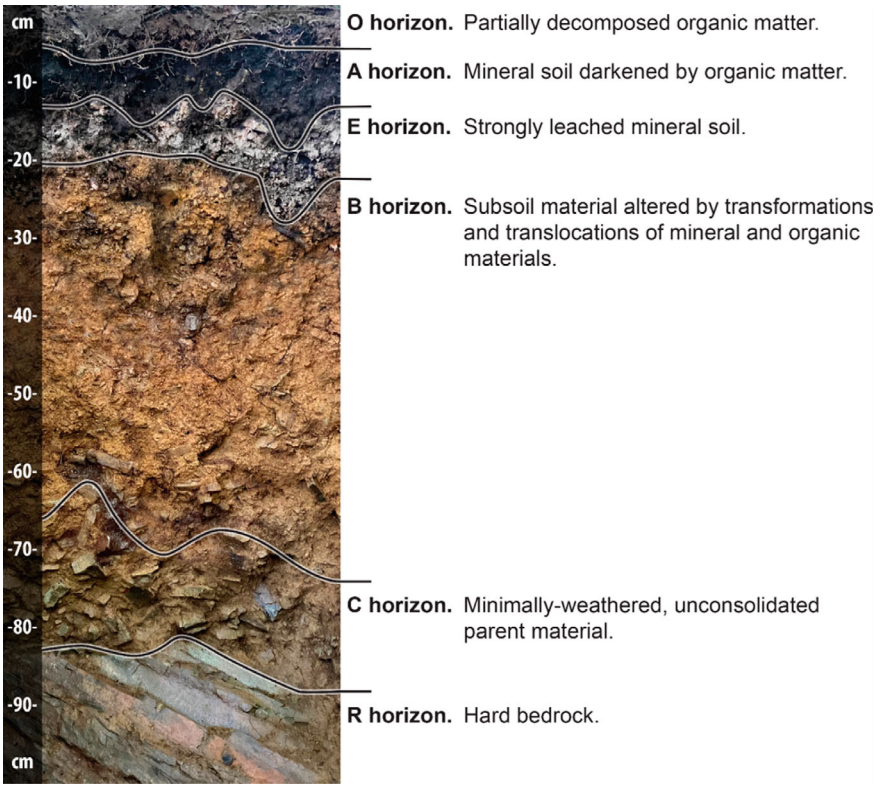


Fig. 3.1 A typical sequence of master horizons frequently observed in high-elevation red spruce (*Picea rubens*) ecosystems (photo by James Leonard)

Sidebar 3.2 Soil Classification We classify soils to improve communication by conveying information about the important characteristics of soils, particularly those properties that we use to make decisions about land use and management. Classification also helps us organize our knowledge about soils by recognizing relationships among the individuals we classify, and it facilitates our inventory and mapping of soil resources. Much like biological classification, Soil Taxonomy is a hierarchical system of classification with soil orders at the highest and most general level, and soil series at the lowest and most specific level. There are currently 12 soil orders recognized in Soil Taxonomy (Soil Survey Staff 2022). Differences among the soil orders are commonly recognized to be associated with differences in climate, vegetation, topography, geology, and/or age. Soil horizons and other diagnostic soil characteristics (e.g., soil moisture regime, soil temperature regime) are used to place a soil into a soil order.

Soil Taxonomy has a unique nomenclature that is used to connote the major characteristics of a soil. Furthermore, unlike biological taxonomy, Soil Taxonomy uses a hierarchical naming structure that helps identify the relationships among soils using unique formative elements to identify soil orders, suborders, great groups, and subgroups. Consequently, names used in Soil Taxonomy include the root elements of the soil order plus formative elements that suggest other distinctive properties of the soil (Table 3.2). As a result, the names of lower-level categories in Soil Taxonomy provide increased specificity about the suitability and limitations of each soil.

Soil orders commonly found in the high-elevation red spruce (*Picea rubens*) ecosystems of the central and southern Appalachians include Spodosols, Inceptisols, Histosols, Ultisols, and Alfisols (Table 3.3). The primary characteristic of Spodosols is that they have well-expressed spodic materials in the subsoil (Soil Survey Staff 2022). Both Ultisols and Alfisols have subsoil horizons with accumulated clays, but Alfisols are inherently more fertile (Soil Survey Staff 2022). Inceptisols show less evidence of soil development than Ultisols and Alfisols (Soil Survey Staff 2022). Additionally, soils that have spodic materials but do not meet the specific requirements of a spodic horizon are often classified as Inceptisols, such as Spodic Dystrudepts (Nauman et al. 2015a, 2015b; Soil Survey Staff 2022). Histosols are dominated by organic soil materials, and are commonly found in wetlands; however, in the high elevations of the central and southern Appalachians where colder temperatures can slow the rates of organic matter decomposition, thick organic layers can accumulate at the surface, and these soils can be classified as Histosols. For more information on soil classification and Soil Taxonomy, refer to the Keys to Soil Taxonomy (Soil Survey Staff 2022) or a soil science textbook.

Soils are described, analyzed, and classified to better understand their inherent properties, limitations, and capabilities to aid in sustainable land management. In this way it is important to recognize the association between soil properties and soil functions. Soil properties, such as pH and porosity, support soil functions, such as biomass production and water storage, which promote ecosystem services, such as supporting food production and regulating the local hydrologic cycle (Adhikari and Hartemink 2016). In fact, soil contributes to multiple provisioning services, regulating services, cultural services, and supporting services, as described in the Millennium Ecosystem Assessment (https://www.millenniumassessment.org/en/Index-2.html).

Specific ecosystem services provided by soils include carbon sequestration, water retention, water purification, flood control, raw materials, habitat, recreation, and aesthetics (Daily et al. 1997; Robinson et al. 2012; Adhikari and Hartemink 2016). Because management and land use actions directly and indirectly influence soil properties, soil functions, and ecosystem services, restoring forests to regain the interconnected functions of an ecosystem, such as with red spruce, is a goal for many managers. More broadly, stewardship of the soil in these and other landscapes

Table 3.2 An example of the hierarchical nature of soil taxonomy using the Mandy soil series (loamy-skeletal, mixed, active, frigid Spodic Dystrudepts)

Level in soil taxonomy	Example taxa	Connotation
Order	Inceptisol	Soils with a weakly developed subsoil with little to no accumulation of clay or other materials
Suborder	Udept	Inceptisol (-ept) in a udic soil moisture regime (ud-)
Great group	Dystrudept	Udept with a relatively acidic pH (dystr-)
Subgroup	Spodic Dystrudept	Dystrudept with a weak expression of spodic materials
Family	Loamy-skeletal, mixed, active, frigid Spodic dystrudept	Spodic Dystrudept where the soil texture of the subsoil is not particularly clayey or sandy (loamy) but has more than 35% rock fragments (skeletal), the mineral content is not dominated by a specific mineral type (mixed), the cation exchange capacity is moderately high (active), and the mean annual soil temperature is between 8 and 15 °C (46 and 59 °F; frigid)
Series	Mandy	Soil series are named after a town or other geographic feature near where the soil was first described
Phase	Mandy channery silt loam, 8–15% slopes	Mandy soils where the texture of the surface horizon is silt loam with more than 15% channers, located on moderately steep slopes

Table 3.3 Soil orders that are commonly found across high elevations of the central and southern Appalachians (Soil Survey Staff 2022)

Soil order	Description/characteristics
Alfisol	Relatively fertile soils formed in humid to subhumid climates; soils have an accumulation of clay (Bt horizons) in the subsoil; commonly found in forested environments
Histosols	Soils comprised primarily of organic materials; often found in cool and/or wet environments where decomposition rates are slow, which allows organic matter to accumulate
Inceptisols	Soils with weakly developed subsoil horizons with little to no accumulation of clay or other materials (Bw horizons); lack of development is commonly attributed to relatively young age or the presence of environmental conditions that inhibit mineral weathering
Spodosols	Soils formed in cool, moist climates under confer forest vegetation; soils have an accumulation of organic matter complexed with Al and/or Fe oxides (Bh, Bs, Bhs horizons)
Ultisols	Relatively infertile soils formed in humid climates; soils have an accumulation of clay (Bt horizons); commonly found in forested environments

contributes to improving the security of the soil resource base (McBratney et al. 2014). An understanding of how the soils in these ecosystems develop and function is needed to effectively incorporate soils information into restoration planning.

3.3 Soils of Red Spruce Ecosystems

Soils develop and evolve in response to climate, vegetation, topography, geology, and age. In the higher elevations of the central and southern Appalachians, the cool, moist climates and acidic parent materials that promote and sustain the characteristic conifer forest vegetation also lead to the development of locally unique soils. For example, the type of vegetation controls the amount and location of organic matter additions to the soil. Red spruce forests produce inherently acidic leaf litter and needles, which decompose more slowly than hardwood leaf litter (Phillips and FitzPatrick 1999; Hobbie et al. 2007). Root secretions of organic acids from conifer vegetation further acidify the soil (Jongmans et al. 1997; Lundström et al. 2000a). This, coupled with the cool moist climates found at higher elevations, often fosters the development of thick organic layers at the soil surface (USDA NRCS 2016a). These organic horizons can range in thickness from <5 cm (2 in) to <1 m (3.3 ft). The needle litter that accumulates in conifer dominated ecosystems accentuates the acidic soil conditions, acting as a positive feedback loop for red spruce regeneration (USDA NRCS 2016a, 2016b).

The thick organic soil layers in red spruce ecosystems produce organic acids that drive a process known as podzolization by which organic compounds bound with iron and aluminum are transported downward in the soil profile and accumulate in the subsoil (Lundström et al. 2000a, 2000b). The accumulation of organic compounds bound with iron and aluminum are what soil scientists recognize as spodic materials. When spodic materials are strongly expressed in the subsoil, that soil is normally classified as a Spodosol in the U.S. system of Soil Taxonomy (Soil Survey Staff 2022), while a soil with weaker expression of spodic materials is recognized as a spodic intergrade of other taxa (see Sidebar 3.2). As a result of the podzolization process, Spodosols are distinguished by thick, dark-colored organic surface horizons, white to gray horizons from which most of the organic matter and secondary minerals have been stripped, and dark red to black spodic horizons that indicate the accumulations of organic matter and/or aluminum and iron compounds in the subsoil (Lundström et al. 2000a). Within the U.S., soils with spodic materials (Spodosols and spodic intergrades) are most associated with the colder and wetter climates of the Pacific Northwest, northern Great Lakes, northern New England, and southern Alaska (Bockheim 2014), although wet Spodosols are also found in coastal zones from New Jersey to Florida. Within the central and southern Appalachians, Spodosols and spodic intergrades are minor components of the landscape (West et al. 2016), relegated to the coldest and wettest areas.

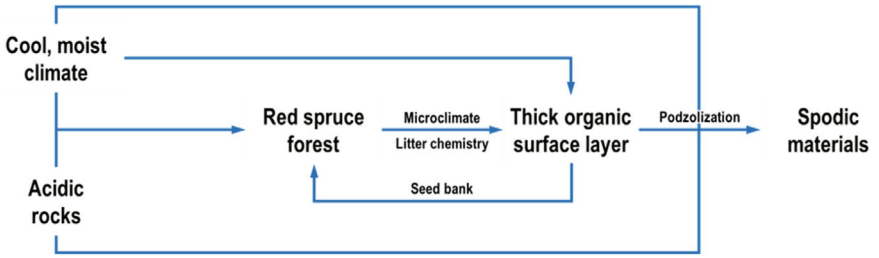


Fig. 3.2 Conceptual diagram showing connections between red spruce (*Picea rubens*) ecosystems and climate, vegetation, geology, and soils. The cool, moist climate and acidic parent materials at high elevations of the central and southern Appalachians favor red spruce over other tree species. The properties of the red spruce litter—along with the cool, moist climatic conditions—promotes the accumulation of thick organic layers at the soil surface. The organic acids released by the slow decomposition of the organic soil materials—in conjunction with the cool, moist climate, and acid parent materials—drive the podzolization process that leads to the development of the organic-rich spodic materials in the subsoil. Those organic soil materials in the forest floor also contain the majority of the red spruce seed bank that enables continued red spruce regeneration

Podzolization is a complex process involving a suite of biogeochemical interactions. The local climate, vegetation, and parent materials all contribute to the development of spodic materials (Lundström et al. 2000a). Consequently, the red spruce ecosystem is intricately connected through the interactions of climate, vegetation, geology, and soils (Fig. 3.2). Variability in site conditions and soil-forming processes influences how strongly or weakly spodic materials are expressed. For instance, a high-elevation ecosystem with base-poor acidic geology would be more conducive to podzolization than a site with alkaline geology. Similarly, changes or shifts in the soil forming factors that drive podzolization (such as a change from conifer to hardwood vegetation) may result in the degradation of spodic materials.

As a result of variations in environmental conditions and soil-forming processes, high-elevation soils across central and southern Appalachia demonstrate varied degrees of expression of spodic materials and other features associated with Spodosols (Fig. 3.3). As the environmental conditions promote more podzolization, the thickness of the organic surface layer increases and the expression of spodic materials increases. Increased podzolization can also lead to the development of a leached layer above the spodic materials (Lundström et al. 2000a, 2000b; Sauer et al. 2007).

Many of the soil functions and associated ecosystem services attributed to the soils in red spruce ecosystems are directly or indirectly derived from the accumulation of organic materials at the soil surface and in the subsoil. Soil organic matter content is a dynamic soil property (Tugel et al. 2005, 2008), which is strongly influenced by both natural processes and human management practices (Lal 2005; Stockman et al. 2013; Ramesh et al 2019). The interactions among soil organic matter and other soil properties and processes are complex (Fig. 3.4). Increasing the amount of organic matter in the soil tends to improve soil structure, decrease bulk density, increase cation exchange capacity, and promote nutrient cycling. Changes to the physical

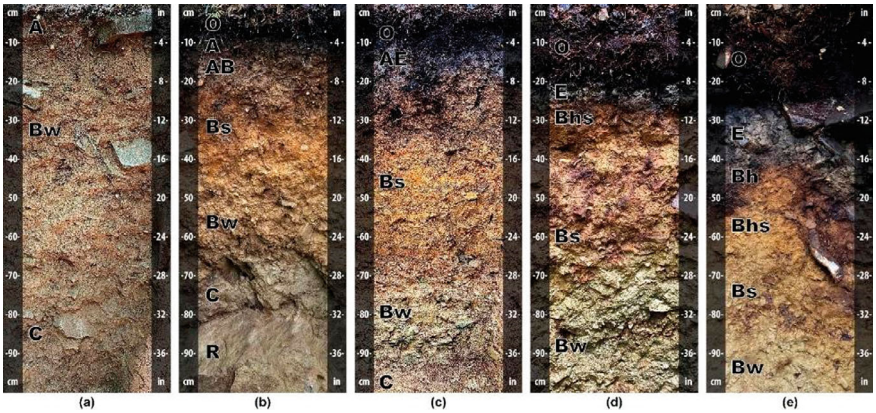


Fig. 3.3 Five soil profiles that depict varying degrees of expression of spodic materials and other features associated with Spodosols in red spruce (*Picea rubens*) forests. From left to right, the thickness of the organic surface layer (O) increases from none to over 20 cm (8 in). Similarly, spodic materials increase from none (Bw) to moderate (Bs) to strong (Bh, Bhs). The development of a leached layer (E) above the spodic materials also increases from left to right. Profiles **b** and **c** are classified as spodic intergrades while profiles **d** and **e** are Spodosols. See Sidebars 3.1 and 3.2 for more information on soil horizon nomenclature and soil classification. Photos by James Leonard

properties in turn increase porosity, increase infiltration, and increase water holding capacity. This can lead to reduced peak flows in streams and rivers, reducing the risk for downstream flooding. Increased organic matter also improves aggregate stability, which reduces soil erodibility and minimizes sediment delivery to surface water. The decomposition of organic matter increases the availability of multiple plant nutrients, particularly nitrogen and phosphorus. Globally, soils contain more carbon than the atmosphere and vegetation combined (Schlesinger and Bernhardt 2013). In central and southern Appalachia, the capacity for red spruce soils to sequester carbon through podzolization makes these forests ideal locations for increasing and maintaining terrestrial carbon stocks while simultaneously improving the various other dynamic soil properties that are influenced by soil organic matter. It also contributes to the region's high biodiversity and makes these soils and these ecosystems more resilient to drought, extreme weather events, or other disturbances.

In both the central and southern Appalachians, the cool, moist climates where precipitation exceeds evapotranspiration favor conifer and ericaceous vegetation and are conducive to the podzolization process. The presence of soils with spodic materials has long been recognized in both the central Appalachians (Williams and Fridley 1931; Coile 1938; Losche and Beverage 1967) and southern Appalachians (Coile 1938; Springer and Elder 1980; Springer 1984; Feldman et al. 1991a, 1991b). However, differences in bedrock geology create different soil-forming environments in the two regions. In the central Appalachians, the soils have formed from sedimentary rocks, particularly acid sandstones and shales. In the southern Appalachians, metamorphic and igneous rocks are the most common soil parent materials, which

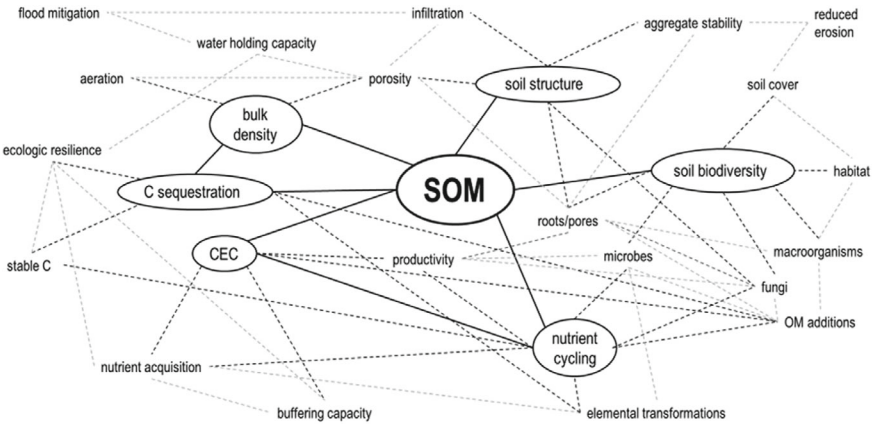


Fig. 3.4 Conceptual diagram illustrating how increasing soil organic matter (SOM) improves water storage, increases nutrient cycling, and enhances ecosystem health, which leads to more resilient landscapes. Solid lines represent primary relationships among soil properties, while dashed lines represent secondary and tertiary relationships

produce soils that are less acidic (Minckler 1939). In the central Appalachians, the most strongly expressed spodic materials are found in sandy and other coarser-textured soils derived from sandstone bedrock, which allow for ample leaching and the movement of the organic acids into the subsoil (Lundström et al. 2000a, 2000b; Sauer et al. 2007; Nauman et al. 2015a, 2015b). While finer-textured soils (i.e., less sand, more silt and clay), such as the soils derived from metamorphic and igneous rocks in the southern Appalachians, may limit podzolization and the expression of spodic materials, recent investigations in the central Appalachians has demonstrated that Spodosols and spodic intergrades can also form in geologies with finer-textured parent materials such as shale geologies (Nauman et al. 2015a).

Another difference in the soil-forming environments between the central and southern Appalachians that may affect the amount of podzolization and, therefore, the strength of expression of spodic materials is the amount of snowfall received and the annual depth of snowpack. Schaetzl et al. (2015) reported that the strength of podzolization in Spodosols in Michigan was related to the thickness of the snowpack and, consequently, the volume of water that enters the soil over a relatively short period of time during spring snowmelt. Compared to the central Appalachians, the highest elevations in the southern Appalachians receive less snowfall and maintain less of a snowpack (Feldman et al. 1991a).

Spodosols and other soils with spodic materials are not the only soils found in red spruce ecosystems of central and southern Appalachia. Bogs, fens, and other wetlands are common across these high elevation ecosystems. The cool temperatures and saturated soil conditions create an environment where organic matter accumulation exceeds decomposition. In some places, these soils are comprised almost entirely of organic materials with little to no mineral soil materials. The high organic matter content of the soils contributes to multiple ecosystem services such as flood control,

water purification, and habitat for endemic plants and animals. Other soils commonly found in red spruce ecosystems include finer-textured soils with accumulations of clay in the subsoil, and more immature soils with minimal soil development. Some of these soils may be wetter, with relatively shallow water tables.

3.4 Impacts of Disturbances on Soils in Red Spruce Ecosystems

The occurrence of red spruce in the central and southern Appalachians has been greatly reduced relative to pre-European settlement (see Chap. 1). In the central Appalachians, up to 99% of the historical range for red spruce was disturbed in some manner between the mid-1800s and early-1900s (Byers et al. 2010). Broad-scale intensive logging and subsequent wildfires in red spruce forests resulted in dramatic changes in tree community composition (Nowacki et al. 2010). Logging of red spruce forests was less prevalent in the southern Appalachians, but atmospheric acid deposition contributed to declines in the 1900s (McLaughlin et al. 1998).

Soil properties and processes were severely impacted by the disturbances, which reduced the ecosystem services the soils could provide. Intensive logging removed the tree canopy, eliminating the organic matter additions that produced and maintained the thick O horizons characteristic of red spruce soils. The loss of forest cover also allowed more solar radiation to reach the soil surface, resulting in warmer temperatures and drier site conditions, which likely facilitated faster decomposition of organic horizons at the soil surface (Allard and Leonard 1952; Pauley 2008; Boggs and McNulty 2010; Fig. 3.5). In some locations, wildfires consumed most of the organic soil materials down to bare rock or the mineral soil surface (Korstian 1937, Allard and Leonard 1952, Clarkson 1964, Lewis 1998; see Sect. 1.2.3 in Chap. 1), resulting in massive CO_2 emissions and the loss of ecosystem services tied to soil organic matter. Landscapes were denuded of vegetation and organic matter after these disturbances, greatly reducing soil water holding capacity across the headwaters of major rivers (Clarkson 1964). The burning of the O horizons also destroyed much of the red spruce seed bank and greatly restricted red spruce regeneration in the burned landscapes (Rentch and Schuler 2018). With no vegetation and no organic horizons to protect the soil from rain-drop impact across steep topography, many areas are believed to have lost some or all topsoil (Korstian 1937; Allard and Leonard 1952). Logging and associated disturbances also modified the physical, chemical, and biological properties of the soil, which contributed to decreased fertility and productivity. More recently, atmospheric acid deposition has further altered the chemistry and fertility of these forest soils (McLaughlin et al. 1998; Elias et al. 2009). Over time, the disturbances had cascading effects that ultimately favored hardwood regeneration (Rentch et al. 2007; Nowacki and Wendt 2010).

Changes in microclimate, specifically increased solar radiation and temperatures, resulted in decreased soil moisture and less leaching. The change from conifer to



Fig. 3.5 Podzolized soil in a former virgin red spruce (*Picea rubens*) forest on Gaudineer Knob, Pocahontas County, West Virginia. The area was logged 20 years prior to this photograph (taken in July 1938) but was not burned. The original O horizon was rapidly decomposed after logging such that only a thin layer (<15 cm [6 in]) of highly decomposed organic material remains at the surface. The leached E horizons and the spodic B horizons that formed under the original red spruce cover are still present. The scale is 30 cm (12 in). See Minckler (1939) for additional information (photo by USDA Forest Service)

hardwood-dominated overstories eliminated the input of organic acids that contribute to the development and maintenance of spodic materials and Spodosols. The degradation of spodic materials, sometimes called depodzolization (Barrett and Schaetzl 1998), became a dominant soil process in the ecosystems where conifer cover was lost. While evidence of podzolization and spodic soil properties has been documented throughout the southern Appalachians, Spodosols do not appear on soil maps, likely because the areas are not extensive enough. Less intensive podzolization may be due to the differences in climate and parent materials, significant depodzolization after the loss of spruce cover, or a combination of both. It may also be due to mapping protocols that did not emphasize or prioritize the identification and delineation of soils with spodic materials. Further investigation is needed to look for possible signatures in the soil of the historic presence of red spruce in the southern Appalachians. This would improve the existing soil maps in these areas and could add to the inventory of recognized ecological sites in the southern Appalachians.

3.5 Red Spruce Ecological Sites

The characteristic soils and landscapes that support the distinguishing plant and animal communities of the high-elevation red spruce forests represent specific ecological sites (ES) across the central and southern Appalachians. Corresponding ES descriptions (ESD) have been developed to better understand the complex relationship between the vegetation, climate, geology, soils, management, and disturbance history of red spruce ecosystems (Fig. 3.2). For a detailed description of ES and the associated ESDs, see Sidebar 3.3. For more on how to use red spruce ESDs to guide management toward reference conditions see Sect. 3.6 and Sect. 8.2.1 in Chap. 8.

Sidebar 3.3 Ecological Site Descriptions Ecological sites (ES) are defined as "a distinctive kind of land based on recurring soil, landform, geological, and climate characteristics that differs from other kinds of land and its ability to produce distinctive kinds and amounts of vegetation and its ability to respond similarly to management actions and natural disturbances" (USDA NRCS 2017). An ecological site description (ESD) is a means for characterizing an ES, and is a tool used to implement practices to meet restoration and management goals for a landscape (Bestelmeyer and Brown 2010). An ES represents a combination of recurring soil, landform, geologic, and climatic influences that produce a unique group of ecological states, which are further comprised of specific community phases.

An important aspect of the utility of ESDs is, in part, a product of correlating one or more soil map unit components to an ES based on observable changes in soil-plant relationships, soil processes, and community composition (Duniway et al. 2010; USDA NRCS 2017). Often, differences between ES and individual ecological states are due to changes in soil properties (Duniway et al. 2010), which affect the potential range of vegetation communities for that site. In practice, an ES is tied to one or more soil map unit components that produce a unique vegetation type (USDA NRCS 2017). These soil map unit components include a soil name as well as other information about the land such as soil texture, slope steepness, or surface rock fragments designators. The relationship between a soil and its associated ESD is very important—if the soil correlated to the ESD is not present, then neither is the ES. One soil map unit component cannot be correlated to more than one ESD, although, a single ESD can have multiple correlated map unit components.

Ecological states are temporally related plant communities and dynamic soil properties that provide recurring structural and functional attributes to a given ecosystem and make up the ES (Bestelmeyer et al. 2009). Of the states comprising an ES, the most important is the reference state. A reference state can be defined as the state that can support the largest number of ecosystem services, and from which every other state in an ES can be derived

(Bestelmeyer et al. 2009; Bestelmeyer and Brown 2010). Often the reference state is accepted as the pre-European conditions that comprise a vegetation community. Throughout much of the eastern U.S., reference states are no longer easily observable due to past anthropogenic disturbances (Drohan and Ireland 2016). Within an ecological state there may be community phases. Community phases are specific plant communities and dynamic soil properties that reoccur in an observable pattern within a state (Briske et al. 2008; Bestelmeyer et al. 2009; Bestelmeyer and Brown 2010). In the reference state there is an associated reference phase community, which imparts structural and functional qualities that determine the reference state's resilience and integrity (Briske et al. 2008; Bestelmeyer and Brown 2010).

Linking ecological states within an ES are what are referred to as restoration and transitional pathways. These pathways represent a suite of restorative management practices that guide the development, or degradational events or processes, that result in a new ecological state. Restoration pathways represent management practices that are used to restore an alternative ecological state back to the reference state condition. A transitional pathway is a degradational pathway attributed to some disturbance. Drought, disease, logging, fires, and many other disturbances affect the trajectory of an ecological community. When extreme disturbances have created highly degraded conditions, restoration back to the reference state of the ES may not be feasible.

The component of an ESD that is most important to management is the state-and-transition model (STM). A STM is a broad conceptual framework used to group together vegetation and soil dynamics inherent to an ES, organized to easily implement restoration and management practices (Briske et al. 2006; Bestelmeyer et al. 2009). A STM provides a way to organize and portray key boundaries that comprise ecological states within an ES, and act as a map for management practices that can be applied to reach a desired ecological result. A STM is composed of ecological states, community phases, and transitional pathways to provide a comprehensive guide for developing management plans specific to a given ES. Triggers, drivers, and disturbance mechanisms that cause transition between states are also conceptually outlined by a STM (Briske et al. 2008; Bestelmeyer et al. 2009). Figure 8.1 in Chap. 8 shows an example of a red spruce ES STM, with ecological states and transitional pathways.

Currently there are two official ESDs for red spruce ecosystems in West Virginia (USDA NRCS 2016a, 2016b). Both ESDs were created for soils developed on shale geologies interbedded with sandstone that produce low pH soils and contain similar vegetation communities; however, both ESDs have now been associated with soils across multiple parent materials derived from sandstone, siltstone, and shale. The primary difference between the two ESs is the vegetation composition and the degree of podzolization specific to the soil associated with each ESD. These ESs are referred to as the Spodic Shale Upland Conifer Forest, which is associated with the Wildell

(classified as loamy-skeletal, mixed, superactive, frigid Typic Haplorthods), Gauley (classified as loamy-skeletal, siliceous, superactive, frigid Typic Haplorthods), and Gaudineer (loamy-skeletal, siliceous, superactive, frigid Typic Haplorthods) soils (see Sidebar 3.2) and the Spodic Intergrade Shale Upland Hardwood and Conifer Forest, which is associated with the Mandy series (loamy-skeletal, mixed, active, frigid Spodic Dystrudepts). A third red spruce ESD, the Rubbly Upland Conifer Forest, has been drafted but it is still in its provisional stages of development. This ESD occurs on the Pottsville sandstone formation and is characterized by a high degree of surface rock fragments. The Rubbly Upland Conifer Forest is correlated mainly to the Gauley, Gaudineer, Blandburg (loamy-skeletal, siliceous, semiactive, frigid Typic Haplorthods), and Leetonia (sandy-skeletal, siliceous, mesic Entic Haplorthods) soils with 15% or more of the soil surface covered with stones or boulders. These three ESs represent a small portion of the range for red spruce within the central and southern Appalachians. Looking ahead, we expect that more ESDs will be developed to further characterize the diversity of red spruce ecosystems in the two regions. These and all other recognized ESDs are publicly available and can be accessed using the Ecosystem Dynamics Interpretive Tool (https://edit.jornada.nmsu.edu).

3.6 Soil Maps as Tools for Decision Making

An inventory of the soil resources of the U.S. has been created by the NRCS as part of the National Cooperative Soil Survey (NCSS). The NRCS is responsible for the management and maintenance of soils information for land use planning across the U.S. This best available data about soil science is continuously updated to reflect new knowledge to ensure that the maps, data, and interpretations are complete, consistent, correct, comprehensive, and current. These resources are publicly available and can be accessed through the Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/).

The Web Soil Survey contains information about specific soil properties and qualities, which can be displayed for user-selected depth ranges, as well as information about how those soil properties may affect various types of management (called interpretations). The tools available within the Web Soil Survey emphasize the critical role that soils have for broad-scale land management and planning. While the information contained in Web Soil Survey can be used to predict or estimate the potentials or limitations of soils for a variety of uses, it is important to recognize that soils can be highly variable over short distances, such that the scale of the soil maps in the Web Soil Survey is not detailed enough to provide site-specific information. Consequently, current soil survey products are most suited for broad land management planning. For these reasons, it is imperative that soil survey information be used alongside any other applicable information such as on-site investigations when making site-specific decisions.

The Web Soil Survey has many uses to support land use and management decision-making. Specific to red spruce restoration efforts, work is underway to tie specific

soils to vegetative communities through the development of ESDs. With the incorporation of ES information, the Web Soil Survey can also be used as a tool to support landscape-scale restoration. A demonstration of the value of the Web Soil Survey for informing red spruce restoration is shown in Fig. 3.6. The upper map (a) shows the base soil map for the area, which is roughly 60 km^2 (23 mi^2; 6 km by 10 km [3.7 mi by 6.2 mi]). The orange lines represent the delineations of the individual soil map units. A map unit may represent one or more dominant soils that are specified in the map unit name (e.g., Mandy-Wildell complex, 35–55% slopes, very stony; MfwF), but also will include smaller areas of other soils. The minor components may or may not influence the use and management interpretations for the areas covered by a given map unit. The middle map (b) depicts the dominant soil order in each map unit delineation. The teal colors on the west side of the map are Spodosols, while the red colors on the east side of the map are Inceptisols (mainly Spodic Dystrudepts). The lower map (c) displays the ESDs associated with the dominant component in each map unit delineation. The dark blue areas, which correspond to the Spodosols, are within the Spodic Shale Upland Conifer Forest ES. The teal areas, which correspond to the Spodic Dystrudepts, are within the Spodic Intergrade Shale Upland Hardwood and Conifer Forest. The purple areas on the west side of the map are within the provisional Rubbly Upland Conifer Forest ES. If the goal was to restore red spruce within this area of interest, the ESDs associated with these three ESs, particularly their STMs, could be used to guide landscape-scale prescriptions for red spruce planting and/or release to guide the current vegetation communities toward the desired state.

3.7 Future of Red Spruce Soils

Red spruce forests within the Appalachians are considered to be one of the most endangered forest types in the U.S. (Noss et al. 1995; Christensen et al. 1996). Interest in red spruce restoration stems from multiple ecological, recreational, biodiversity, and carbon mitigation interests. Red spruce forests provide habitat for threatened, endangered, and sensitive species such as the Cheat Mountain salamander (*Plethodon nettingi*; Pauley 2008) and Virginia northern flying squirrel (*Glaucomys sabrinus fuscus*; Menzel et al. 2004). The soils that form as part of red spruce ecosystems also provide valuable ecosystem services including increased water holding capacity and filtration (Sauer et al. 2007) and soil carbon buildup both at the soil surface and in the subsoil (Herbauts and De Buyl 1981; Miles 1985; Sohet et al. 1988; Tarnocai et al. 2009; Averill et al. 2014). Restoration of red spruce forests across the central and southern Appalachians is essential to building ecological resiliency across the landscape. Research suggests that red spruce restoration efforts can sequester significant soil organic carbon at the soil surface in less than 100 years (Nauman et al. 2015b), and is also expected to increase soil organic carbon in the spodic materials in the subsoil (Barrett and Schaetzl 1998; Lundström et al. 2000a, 2000b) (Fig. 3.7). Available ESDs developed for red spruce ecosystems (e.g., USDA NRCS 2016a, 2016b) can be used to inform potential carbon sequestration during forest restoration

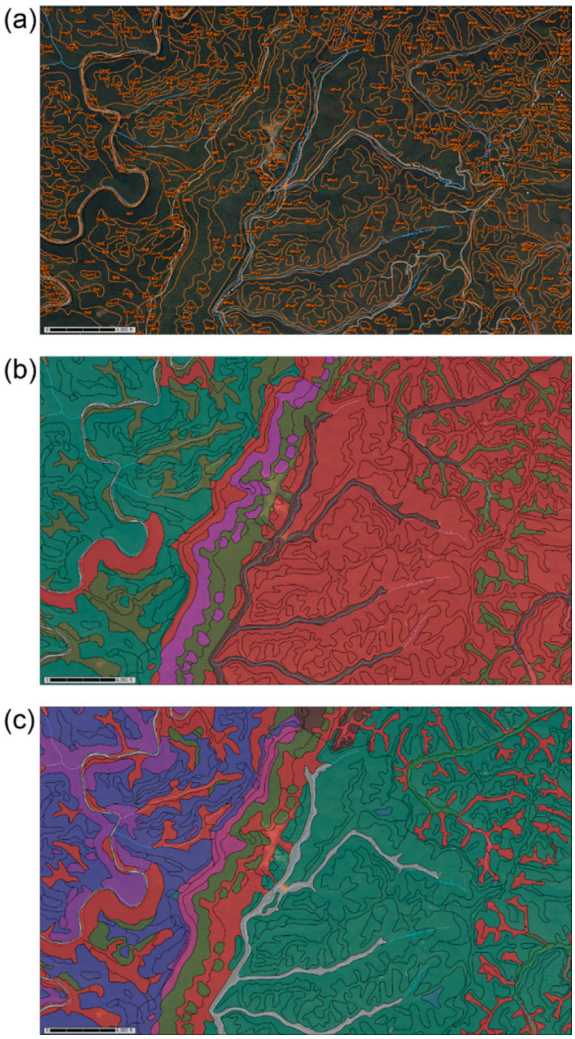


Fig. 3.6 Example of the value of the web soil survey for informing red spruce (*Picea rubens*) restoration, using a 60 km^2 (23 mi^2) area near Wildell, West Virginia. Soil map units, **a** represent one or more dominant soils that are specified in the map unit name. Soil orders, **b** depict the dominant soil in each map unit delineation (teal: Spodosols; red: Inceptisols; green: Ultisols; purple: Alfisols; gray: Entisols). Ecological sites, **c** indicate the ecological site description (ESD) associated with the dominant component in each map unit delineation (blue: Spodic Shale Upland Conifer Forest; teal: Spodic Intergrade Shale Upland Hardwood and Conifer Forest; red: Convergent Uplands; purple: Rubbly Upland Conifer Forest; green: Divergent Uplands; brown: Acidic Shale Upland Oak/Heath, magenta: Frigid High Elevation Uplands). By associating soil map units with specific ESDs (and their associated STMs), landowners and managers can use soil maps for a given area of interest to develop management plans to meet restoration or conservation goals

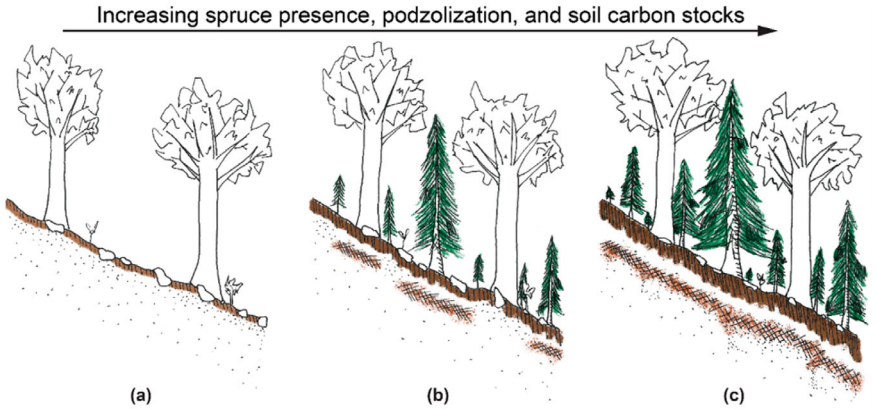


Fig. 3.7 Illustration showing that as the red spruce (*Picea rubens*) component of ecosystems increases, the soil organic carbon stocks (indicated by dark shading) also increase at the soil surface and in the subsoil. The greater presence of red spruce leads to increased thickness of the forest floor. The organic acids that leach from the forest floor promote more podzolization and greater accumulation of organic carbon in the subsurface through the formation of spodic horizons

activities, with initial investigations showing that soils of the Spodic Shale Upland Conifer Forest contain greater soil organic carbon stocks than the Spodic Intergrade Shale Upland Hardwood and Conifer Forest, but greater opportunities for increasing carbon stocks in the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (Leonard 2022).

In general, environments that alter the types and amounts of processes that occur in soil can create persistent features that record the history of the environment in which they formed, even after those environmental conditions have changed. Consequently, every soil has a story to tell through the horizons and the associated colors, textures, structures, and other properties we observe (Targulian and Goryachkin 2010; Lin 2011; Monger and Rachal 2013). In the central and southern Appalachians, the presence or absence of spodic materials, including how strongly or weakly they are expressed, serve as a record of historical site conditions, referred to as pedomemory (Nauman et al. 2015a). This information can be observed directly in the field when investigating possible sites for restoration efforts, and it can be inferred when examining soil maps from across the region. A Spodosol with well-expressed spodic morphology indicates that red spruce or other conifers were dominant historically, even if conifers are a limited or absent component in the stand today. The absence of spodic properties, however, may not necessarily indicate that red spruce was never there historically; it may indicate that other conditions were not conducive to podzolization or that site conditions promoted more rapid depodzolization. The lack of spodic materials provides useful information too because if a site did not support red spruce in the past, it is likely not conducive to contemporary red spruce restoration efforts. To summarize, spodic properties and the degree to which they are expressed is a valuable land management tool in planning and prioritizing red

spruce restoration across the central and southern Appalachians. Soil maps, with their associated ESDs, are particularly useful for targeting restoration efforts at the scale of landscapes to regions. For site-specific assessments, or where existing soil maps lack either the necessary detail or the necessary ESDs, an investigation of the soils can reveal the presence or absence of spodic materials.

Today, red spruce ecosystems only occupy a fraction of their historical range (see Chap. 1). Furthermore, forest impact models predict that habitat quality will decrease for red spruce in the central Appalachians over the next few decades (Butler et al. 2015; see Chap. 7). Thus, the challenge of restoring red spruce ecosystems in the central and southern Appalachians is a daunting one. Deciding where to focus red spruce restoration efforts within the current geographic distribution of the species is even more challenging. Although long-gone, historical red spruce forests left signatures in the soil. This pedomemory, when utilized in conjunction with topographic conditions and climatic projections, can serve as an effective tool for land managers when prioritizing where to focus red spruce restoration across the landscape.

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