CHAPTER 1
Soil Foundations

OVERVIEW

The forests of the world are shaped by the soils that support them, and the soils are in turn shaped by the trees. Soils change substantially across landscapes, in response to changes in the parent materials in which soils form, to differences in water flow, and the responses of plants and the rest of the ecosystem biota. Differences in soils lead to large differences in the species composition and growth rates of forests, largely mediated by the supply of water, nutrients, and sometimes oxygen in the soils. One of the most characteristic features of forest soils is the O horizon, the commonly occurring uppermost soil layer composed of fresh litter, decaying litter, roots, and soil organisms. The tapestry of our current understanding of forest soil comes from threads that reach far back into nineteenth century, with great detail added from the advances of science in the twentieth century. The broad variety of soils and forests across dimensions of space and time can be investigated with three standard questions: what's up with this soil, how did it get that way, and what will it likely be in the future?

EVERYTHING IN FORESTS AND FORESTRY CONNECTS TO SOILS

A century ago, Aaltonen (1919) published a classic assessment of Finnish forests, and he concluded that understory regeneration of pine trees was limited when overstory trees were present. The apparent inhibition of small trees by large trees extended too far away from the large trees for the suppression to be about shading, and Aaltonen concluded that the key issue must be about competition for soil resources rather than for light (Figure 1.1). If Aaltonen was right, then trenching small plots to cut off competition for soil water and nutrients with surrounding trees should stimulate the regenerating trees. This is exactly what happened in tests around the world: removing belowground competition for water and nutrients leads to large increases in growth of understory plants even when shaded by healthy overstory canopies. Competition for light is of course important for plants too, but the classic forestry idea of "shade tolerance" is often as much about soil resources as about light (Coomes and Grubb 2000). Ancient ideas about single resources limiting the growth of trees need to be left in the past. The production of most plants and ecosystems is limited by more than one resource, and almost always limited by one or more resources found in soils.

FOREST SOILS HERE ARE DIFFERENT FROM OVER THERE

Across Union County, South Carolina in the southeastern United States, plantations of loblolly pine differ in growth rates by more than twofold. About 15% of the land can grow less than 5 m^3 ha^{-1} $year^{-1}$

Ecology and Management of Forest Soils, Fifth Edition. Dan Binkley and Richard F. Fisher.

Figure 1.1 The regeneration of pine seedlings in Finland was inhibited by mature trees, at distances that were too great to be competition for light. Aaltonen (1919, after the description from Kuuluvainen and Ylläsjärvi 2011) concluded that the issue must be competition for soil resources. Experimentation beneath full canopies of loblolly and shortleaf pine trees in Duke Forest showed that removing competition for soil resources by trenching plots led to huge growth responses by understory herbs and tree seedlings (center left, before trenching, center right, four years after trenching; after Korstian and Coile 1938). Shade is much deeper under mature canopies of Norway spruce, giving the impression there is only enough light to support an understory of mosses. However, trenching a small plot within the dark stand of Norway spruce in Bavaria, Germany, led to prolific growth of understory vascular plants (*Source:* lower photo, from Christian Ammer), just like the classic study of Fabricius (1927) who found trenching under a spruce stand more than tripled growth of understory oak and hornbeam seedlings.

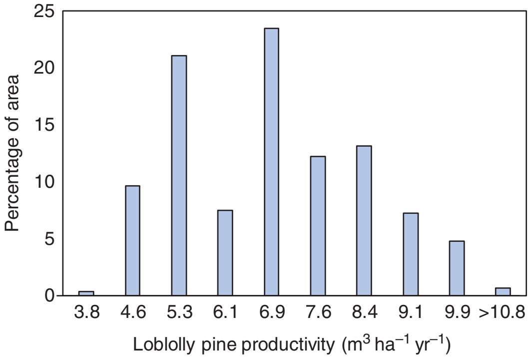

Figure 1.2 Across 100,000 ha of Union County, South Carolina in the southeastern United States, the growth rate (productivity) of wood in loblolly pine plantations differ by more than twofold. The climate is the same for all locations, so the differences in growth rate result from differences in soils (*Source:* from data of the Natural Resource Conservation Service (2017)).

of wood, and about 15% can grow more than 9 m^3 ha^{-1} $year^{-1}$ (Figure 1.2). The climate doesn't vary across the County, so what drives the differences in ecosystem productivity? Of course, soils provide the key explanation. The soils across the County vary in capabilities of supplying water and nutrients to support tree growth. Some of these variations result from factors that influence soil development over very long periods of time, such as the original parent material and position on slopes (near the top where water and nutrients are removed, or near the bottom where water and nutrients accumulate). As with most aspects of soils, changes in some factors (such as parent material or water supply) cascade with follow-on changes in soil chemistry, the biotic community, and the growth of plants.

CURRENT FOREST GROWTH IS LIMITED BY SOIL RESOURCES ACROSS REGIONS

Just as productivity differs across locations, the productivity within a single location may shift upward or downward if soil conditions change. At the sub-continent scale of the southeastern United States, the growth of loblolly pine plantations differs by more than twofold from one region to another (Figure 1.3). The spatial pattern of growth differences connects to temporal patterns too: the ability of soils to support tree growth can change over time, in response to active or passive management. Estimates of the climate-determined potential productivity across the region can be compared with the observed rates, and the differences between these two suggest that soil-related factors restrain growth by 15–20% across the region. Silvicultural practices can move forest growth toward the climatic potential, or indeed reduce growth further if done poorly.

SOILS SHAPE FORESTS, AND FOREST SHAPE SOILS

The two forests in Figure 1.4 are growing only 50 m apart, along the Mendocino Coast in California, USA. The tall forest has fast-growing Douglas-fir, redwood and Bishop pine trees. The short forest has slender stems of Bishop pine, Bolander pine, and pygmy cypress. What ecological factors explain such huge differences in vegetation? Differences in weather and climate would not be important, as the forests experience the same conditions. Some other possibilities that might come to mind include forest age (perhaps one type of forest is much older), the influence of recent fires (perhaps the short forest was a tall one before a fire?), or a legacy of logging. Given the focus of this book, it's not surprising that the key differences are in the soils. The tall forest grows on a deep soil with good properties for supplying oxygen and nutrients to the trees. The short forest is on a soil with a cemented layer that restricts water movement, and the high water table impairs the supply of oxygen for roots and the soil biotic community (Figure 1.5).

But why are the soils so different? Have the soils been developing for different periods of time, or did they develop from different initial rock types? Or is it possible that they could be the same age, developed

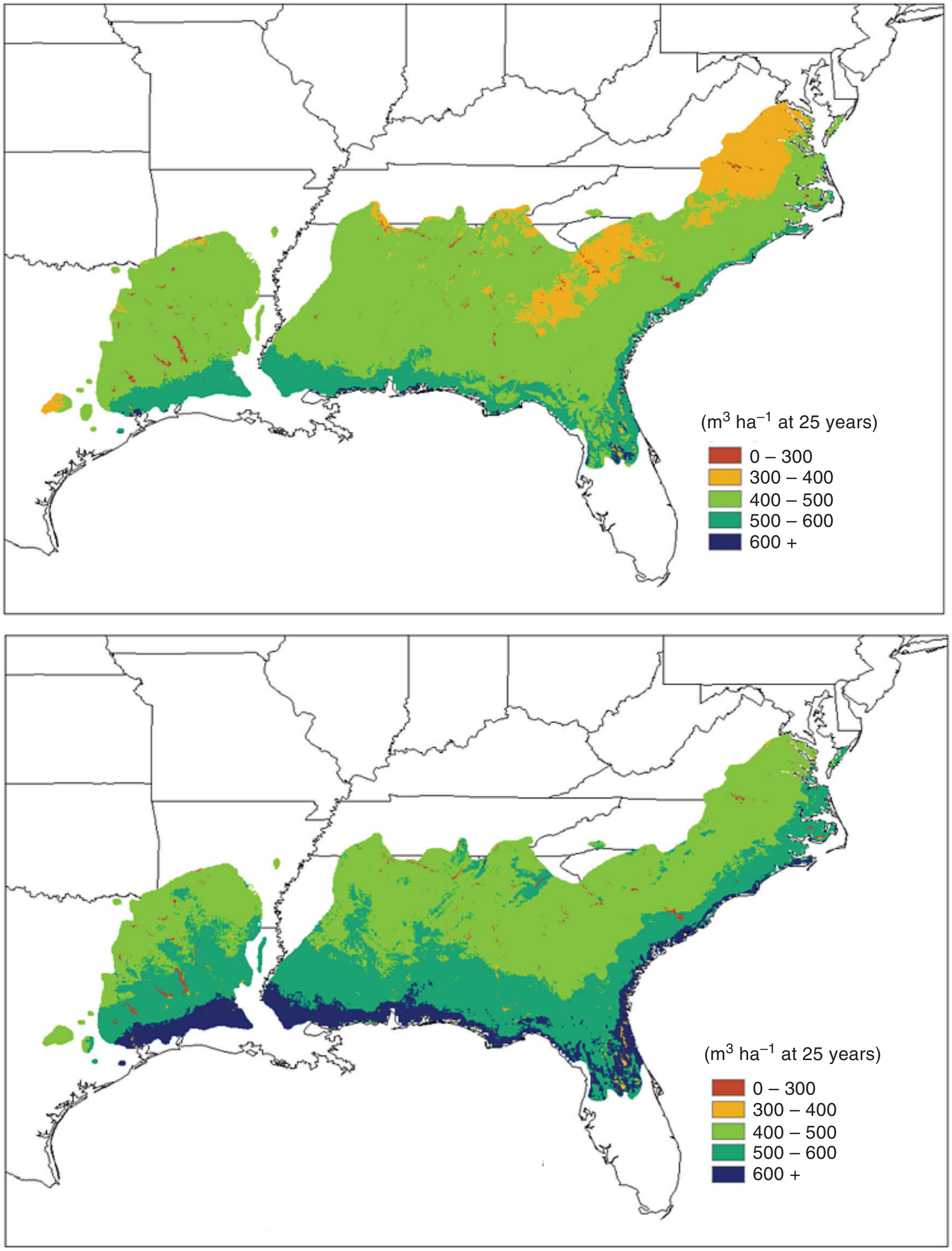

Figure 1.3 The accumulation of stemwood in loblolly pine plantations in the Southeastern United States ranges from about 300 to 600 m^3 ha^{-1} of wood volume at age 25 (upper graph). If soil fertility did not limit growth, many locations would show much higher productivity (middle graph). Across much of the region, current limits on soil fertility reduce forest stem biomass by about 60–90 m^3 ha^{-1} (a reduction of 15–20%; lower graph). These graphs based on illustrative simulations using the 3PG model, provided by Jose Alvarez-Munoz.

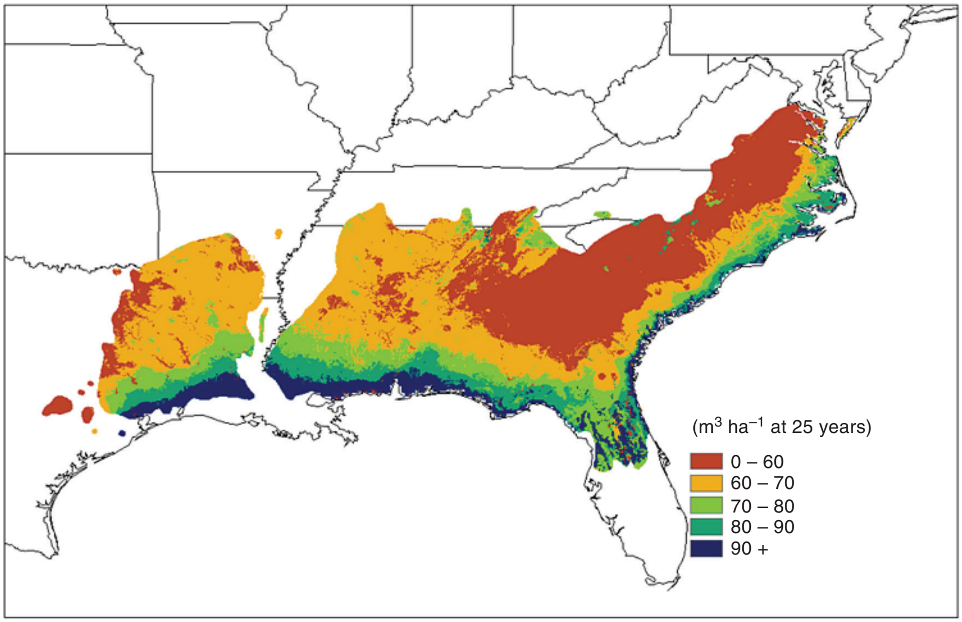

Figure 1.3 (Continued)

Figure 1.4 These two forests are part of the Ecological Staircase in the Jughandle State Park along the California coast. Differences in soils lead to differences in vegetation and tree sizes (Jenny 1973; Binkley 2015; *Source:* photo on left from Ron Amundson, on right from Sarah Bisbing).

Figure 1.5 The soils under the tall trees (left) is well drained, with good supplies of oxygen for tree roots and the soil biotic community. The soil that supports only short trees (right) developed an iron-cemented layer that keep water perched high in the profile, restricting oxygen, root growth, and nutrient cycling rates (Jenny 1973; Binkley 2015; *Source:* photos by Ron Amundson).

from the same initial materials, and some other factor explains these differences? The development of soils always involves complex, interacting processes. An understanding of chemistry, physics, biology and ecology is required to understand how soils develop in different ways, and how these differences shape forests. In this case, the key feature that led to such different sorts of soils was the location relative to the edge of a terrace; water drained away better the locations supporting tall trees, and water flow was more restricted back from the terrace edge where only the short trees can grow.

The comparison of these two adjacent sites also illustrates a key feature of forest soils, and a key challenge in studying these systems. As the forests and soils began developing, the current rate of input of organic matter and leaching of minerals was probably rather similar. Only small differences in the transport of iron would have occurred in any single year. Yet the cumulative outcome of so many years with minor differences was the vastly different soils we see today. This theme comes up in other aspects of the study of forest soils. A short-term study that lasts two or five years on the rates of decomposition of litter might conclude that the litter of decomposes more quickly at one site than another. This might be interesting, but the long-term development of the soil would depend on the very small fraction of the litter material that enters long-term pools that are protected from decomposition. We would not have a reason to expect (or evidence to support) that the initial rates of decomposition have any relationship to the important processes that determine long-term C accumulation. Rates of rapid processes may be easy to measure, but important changes in soils generally develop from slow processes that have little effect in any single year.

This book explores the fascinating array of the minerals, organic matter, and organisms that inhabit and shape soils, providing a foundation for understanding the forests that grow in theses soils – and how forests continue to shape soils.

SOILS ARE BOTH THE MOTHERS AND THE CHILDREN OF FORESTS

Forests change at rates that are fast enough for us to see, over the course of a decade or a few decades. Soils change at about the same rate, but the changes aren't so visible to our eyes. The changes in these components of the whole forest ecosystem result from mutual interactions between trees and the soils that support them.

New forests commonly establish on soils that supported many generations of forests in the past. The soils provide reservoirs of water that trees depend on between storms, and stocks of all the major nutrients that form the building blocks of the trees' biochemicals. While the soils are supporting the trees, the trees are changing the soils in subtle and dramatic ways. Trees pump high-energy organic compounds into the soil, from both roots and aboveground tissues. They can also pump nutrients from one location in the soil to another, changing the nutrient profiles both laterally and vertically. The organic compounds (organic matter) fuel the phenomenal soil community of animals and microbes that transform the composition and structure of the soil. Understanding forest trees requires insights about soils, and understanding soils requires insights about trees and the rest of the biotic communities.

In the broadest sense, a forest soil is any soil that has developed primarily under the influence of trees. Trees may sink roots deeper than other types of plants, and they produce large amounts of complex organic compounds that take a long time to decompose. A key feature of most forest soils is the development of a layer of organic material at the top: the O horizon. Forest soils cover more than a third of the Earth's land area, though in many locations the forests were removed and the soils converted to uses. Perhaps as much as one-third of the Earth's former forest soils are now devoted to agricultural, urban, or industrial use.

Soils that develop in forests often differ strikingly from other types of ecosystems. Soils that are too dry to support trees typically lack a consistent O horizon, have high concentrations of salts, and horizons cemented by calcium carbonate. Agricultural soils are routinely managed by plowing, homogenizing the upper soil and removing the legacies of three-dimensional structure that characterize forest soils. Some grasslands are present in areas that are wet enough to support trees, but fires or other processes support the dominance of grasses. Grassland ecosystems tend to support different sorts of biotic communities that lead to different soil composition and structure, including a top horizon rich in both organic and mineral materials.

Many formerly forested soils are now in other land uses, and most of the soils that remain under forests have been modified to some extent by humans over recent millennia. The production of food has relied upon soils that were formerly under trees and grasses. The clearing of forests historically entailed "slash and burn" land use. Trees were felled and burned to provide fertile, weed-free fields for food crops. After several years, the invasion of other plant species (weeds) lowered the production of food, leading to abandonment and regrowth of trees. With the development of urban societies, soils could be harnessed permanently for agriculture, as available labor could control weeds (and provide some nutrition management by recycling organic wastes). In more recent times, industrialization around the world consumed vast quantities of wood for fuel and building material. Harvested forests typically regrew, though in some notable situations the removal of trees led to long-term deforestation.

Wood from forests provided the fuel to develop civilization, and rates of wood removal for fuel and wood products did not plateau until the 1990s, when worldwide wood use stabilized at about 3.5 billion m^3 ha^{-1} $year^{-1}$ (Sutton 2014). When the first edition of this book appeared in the 1970s, more than half of that wood supply was taken from "natural" forests, where direct forest management was limited. Planted forests now provide over half of the annual wood harvested from the world's forests, as the area of plantations increased almost 50%. The most intensively managed forests account for just 1.5% of all forest area, but the soils of these plantations produce one-third of the wood used for paper and solid wood products (INDUFOR 2012; Binkley et al. 2017).

Humans have influenced forest soils even in some situations where harvesting has not occurred. Most forests experience fires, mild or severe, on time scales of a few years to several centuries or more. Humans have altered the occurrence of fires in many ways, including changing the structure of fuels in forests (by intensive grazing), and by providing the spark to light fires (more often than lightning does).

Other human-related influence on unharvested forests may be as large as the changes in fires. Tree species have been introduced into forests from around the globe, but even more important has been the spread of tree-damaging insects and pathogens. The major tree species in the eastern part of North America was the American chestnut, but the exotic chestnut blight essentially removed chestnuts from the continent. American elm trees were codominant across much of the same region, but they have been largely removed by exotic Dutch elm disease.

Human-induced changes in the atmosphere also influence forests. Most forests of the planet receive much more nitrogen in rainfall than in historical times, and increased supplies of this often-limiting nutrient can spur the growth of some trees at the expense of others. Climbing concentrations of carbon dioxide in the atmosphere are warming the planet and shifting precipitation patterns.

All these human-related changes in forests and forest soils may seem to paint a dire future. Fortunately, both forests and forest soils are remarkably dynamic and resilient, and both will continue to support the planet's future, though future forests and soils will not be the same as those in past eras.

FOREST SOILS DIFFER IN MANY WAYS FROM CULTIVATED SOILS

Soils are much more than just the basement of forests, and more than a provider of water and nutrients. Soils are dynamic systems comprised of thousands-to-millions of types of organisms, taking in energy and matter and releasing heat, gasses, and chemical byproducts that remain in the soil. These dynamic systems exist in four dimensions: the usual two dimensions associated with the Earth's surface, the depth below the surface, and the dimension of time over which soil-shaping processes occur.

The distinctions between wildland forest soils and soils that have been strongly influenced by cultivation might be illustrated best with a pair of pictures (Figure 1.6). The legacies of agricultural cropping of soils go far beyond issues of maintaining soil organic matter and nutrients. Forest soils typically show strong structural differences across small distances, as long-term patterns of soil roots, animal burrowing, and water percolation develop cumulative legacies that may become larger, perhaps being reset partially when soils are stirred by the blowdown of trees with large root systems (for example, Figure 6.2).

FOREST SOIL SCIENCE IS AS OLD AS SOIL SCIENCE ITSELF

The circular nature of the interactions between trees and soils may seem obvious today, but insights about these intimate interactions were rather slow in

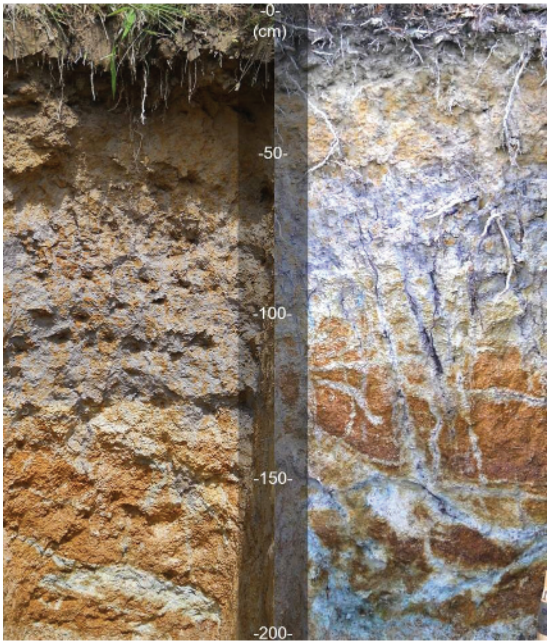

Figure 1.6 These soil profiles come from pits that are only 25 m apart in the Duke Forest in North Carolina, USA. A few centuries ago, the profiles would have been the same. Both were cleared and cropped with corn and tobacco in the 1700s and 1800s. The soil on the right was planted with pine trees about 1900, and the soil on the left was maintained in grass/forb vegetation (as part of a powerline right of way). The pine trees restored the 3-dimensional structure of the soil, including legacies of root channels. Areas with higher concentrations of oxygen in the soil atmosphere are orange, and those with lower concentrations are gray. Channels formed by roots can provide for rapid transport of both air, water, and dissolved chemicals, influencing soil chemistry and ecology at scales of millimeters to tens of meters (*Source:* photo from Allan Bacon).

developing over past centuries. Early insights into soils would have largely been based on empirical experiences with little ability to explain *why* the fertility of one soil exceeded another. Early natural philosophers in the West who pondered the connections between plants and soils included Aristotle (384–322 BCE), Theophrastus (372–297 BCE), Cato (234–149 BCE), Varo (116–27 BCE), and Virgil (70–19 BCE). Pliny the Elder (23–79 CE) gave the most complete account of the ancients' understanding of soil as a medium for plant growth, including crops and forests. He chronicled folk wisdom and other empirically derived information. Many farmers recognized that certain crops were more productive on certain sites or soils, and that legumes may improve soil fertility. Not much insight about soils developed over the next millennium in the West. Scientific approaches finally began to take seed, and in 1563 Bernard de Palissy published a treatise *On Various Salts in Agriculture*, in which he stated that soil is the source of mineral nutrients for plants. However, his work had little impact on other natural philosophers.

The period from 1630 to 1750 saw the great search for the "principle of vegetation." During this time, natural philosophers conceived of matter as comprised of four (or five) "elements": fire, air, water, and earth (and perhaps niter [potassium nitrate]). Van Helmont (1577–1644) conducted a classic experiment with a willow *(Salix)* tree: he grew 164 pounds of willow tree in 200 pounds of soil in a pot, and at the end of the experiment he measured that the soil in the pot had lost only 2 oz. Since only water had been added during the experiment, he concluded that the 164 pounds of willow had come from water alone. Van Helmont may not have been the first to conduct this experiment and draw the wrong conclusion. A similar experiment was conducted and similar conclusions were also drawn by Nicholas of Cusa (1401–1446). Robert Boyle later repeated the experiment with *Cucurbita*, obtained similar results, and reached the same mistaken conclusion.

Despite the apparently definitive experiments of Van Helmont and Boyle, the quest for the principle of vegetation continued. John Woodward (1699) grew *Mentha* in rainwater, in water from the River Thames water, in sewage Hyde Park, or in sewage mixed with soil. He found that the plants grew better as the amount of "sediment" increased, and concluded that "certain peculiar terrestrial matter" was the principle of growth. Frances Home experimented and reached similar conclusions in the 1750s. Home went on to note that "exhausted soils recovered from exposure to the air alone" and therefore concluded that the air must be the ultimate source of the essential materials.

It was not until 1804 that de Saussure successfully explained the origin of the material comprising plants. He found that most of the mass of the plant was carbon derived from the carbon dioxide of the air. Interestingly, we have found in our teaching that fewer than half of the undergraduate and graduate students taking basic and advanced courses in ecology understand that the majority of the mass of plants derives from the air, not from the soil or water!

The work of de Saussure and Boussingault in France in the early nineteenth century began a period of rapid scientific advancement. In 1840, Justus von Liebig in Germany published *Chemistry Applied to Agriculture and Physiology*, and modern soil science began. Liebig helped dispel the theory that plants obtained their carbon from the soil and developed the concept that mineral elements from the soil and added manure are essential for plant growth. However, Liebig erroneously believed that plants received their nitrogen from the air rather than from within soils (as demonstrated by de Saussure). Lawes and Gilbert put these European theories to test at the now-famous Rothamsted Experiment Station in England and found them to be generally sound.

Following the work of these chemists, scientists in many different fields including geology (Dokuchaev, Hilgard, Glinka), microbiology (Beijerinck, Winogradsky), and forestry (Grebe, Ebermayer, Muller, Gedroiz) contributed to the development of what today is termed “soil science.” Most of the early research on soils was directed to its use for agricultural purposes because Europe had a critical food shortage.

The importance of soils to forest ecosystems was recognized by several early scientists. In 1840, Grebe, a German forester, stated: “In short, almost all of the forest characteristics depend on the soil, and hence, intelligent silviculture can only be based upon a careful study of the site conditions.” Pfeil echoed this thought in 1860, and it became a central theme of European forestry (Fernow 1907). Gilbert (1877) examined how soils developed in relation to geology across landscapes that varied in parent material and topography. Hilgard (1906) recognized a relationship between vegetation and soils in North America similar to the relationship that had been noted in Europe. The work of Grebe, Pfeil, Hilgard, and others, perhaps unintentionally, laid the foundations of forest ecology. In North America, early ecologists such as Merriam (1898), Cowles (1899), and Clements (1916) knew that soil was important in vegetation dynamics, but none of them understood soils well. Toumey (1916) noted the importance of soils in American silviculture for the first time.

Early research in forest soils was dominated by basic scientific studies. In fact, some very important early soil science research was done on forest soils. Ebermayer’s work on forest litter and soil organic matter (1876) had a strong influence on soil science and agriculture. Muller’s work on humus forms (1878) marked the beginning of the study of soil biology and biochemistry. Gedroiz (1912) pioneered work on soil colloids, suggesting that soils performed important exchange reactions, and laid the groundwork for modern soil chemistry. These scientists were interested not only in soil properties, but also in the processes that led to the existence of the properties.

Scientific curiosity about forest soils developed more application late in the nineteenth century as wood production became a pressing problem in Europe, and the restoration of degraded forestlands abandoned after agriculture became a necessity in North America. Forest soils research in the twentieth century was dominated by studies focusing on species selection for reforestation, methods of site preparation for reforestation, methods for estimating the productive capacity of forest lands, tree nutrition and response to fertilization, and soil changes under intensive forest management. Late in the twentieth century, new interests developed in the areas of impact of deposition of acidity and nutrients from air pollution, and sustainability of forests facing intensive harvesting (for biofuels and short-rotation forestry).

Education about forest soils developed in parallel with advances in scientific understanding. In

Germany, H. Cotta emphasized that soils were a key to forest production as early as 1809. Forestry textbooks began to include information on soils, including Grebe (1852) and B. Cotta (1852). The first text devoted to forest soils was published in 1893 by Raman, and the first French text by Henry (1908), with continuing production of forest soils texts across Europe (including Remezov and Progrebnyak 1965).

Forest soil science developed more slowly in North America, perhaps of the lack of concern was because forests seemed to be inexhaustible. Only after World War I did the ideas of managing selected forests for sustained yields, reforestation of abandoned farmlands, and the establishment of shelterbelts in the Midwest begin to take hold. The first soils textbooks to appear in North America came along only after World War II, from Wilde (1946 and 1958) and Lutz and Chandler (1946). Coile (1952) provided an overview of the connection between soil properties and tree growth (for more background on the development of forest soils in North America, see Gessel and Harrison 1995). A hiatus in forest soils texts in North America lasted until the late 1970s, when Armson (1977) published a text in Canada, and Pritchett (1979) published the first edition of this text.

THREE FUNDAMENTAL QUESTIONS APPLY TO EVERY FOREST SOIL

Each forest soil is a unique, incredibly complex system. Indeed, the idea of any single, discrete forest soil is an oversimplification of the scales of space and time where many rapid and slow processes shape and reshape the soil system. This complexity may be daunting, and we certainly cannot understand all the intricacies of forest soils. Fortunately we can examine and understand many key aspects, with a combination of clear thinking and appropriate measurement techniques. Three questions might be helpful when trying to understand the soil for any particular forest or location within a forest:

1. What's up with this forest soil? This question leads us to characterize the structure of the soil, the biotic community shaping the soil, and the chemistry of interactions.
2. How did this forest soil get that way? All forest soils have developed over varying periods of time, under the influence of many processes. Some processes and factors may be much more important than others in determining the development of soils over short terms and very long periods. Identifying the important factors that shaped the history of a soil may provide the foundation for understanding the soil's current condition and launch into the third question.
3. What's next for this forest soil? Sustaining or enhancing the ability of soils to grow plants is a nearly universal goal for people who work in forestry (and agriculture). The future trajectory of a soil depends on its current state (Question 1), and insights about the soils development (Question 2) are crucial. The future of a forest soil depends very heavily on what events and impacts will happen, and these are especially important for managed forests.

IDEAS, MEASUREMENTS, AND CLEAR THINKING ABOUT EVIDENCE CAN ANSWER THE THREE QUESTIONS

The application of the three questions will always entail a combination of ideas we have learned from other people and other soils, and direct information about each soil. Some of these ideas are likely to be fairly solid representations of how the world really works, and as in all sciences some ideas are likely to fail to capture the real story. Similarly, some of the "direct" information we have about a soil may be biased (for example, emphasizing the top-most soil and missing key features deeper below the surface) or extrapolated imperfectly (such as applying a single soil texture across a hectare, glossing over variations within the hectare). The most robust insights and management of forest soils may depend on taking an "evidence-based" approach. Evidence-based approaches (whether formal or informal) carefully spell out how much an idea is based on reasoning and how much on the results of measurements and experiments. These approaches also explicitly recognize that evidence and insight gained for one soil or landscape will not necessarily fit perfectly with another soil or landscape. General knowledge of forest soils can be applied most usefully to specific forest soils when the strength of evidence is articulated clearly. The following chapters develop the ideas needed to understand the composition and processes that comprise forest soils, and how evidence-based approaches continually improve our insights about fascinating forest soils.