GLOBAL EDITION

The Nature and Properties of Soils

FIFTEENTH EDITION

Ray R. Weil • Nyle C. Brady

Pearson

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To all the students and colleagues in soil science who have shared their inspirations, camaraderie, and deep love of the Earth.

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Nyle C. Brady 1920–2015

On 24 November 2015 soil science lost one of its giants. Nyle C. Brady passed away at the age of 95. Dr. Brady was a global leader in soil science, in agriculture, and in humanity. He was born in 1920 in the tiny rural town of Manassa, Colorado, USA. He earned a BS degree in chemistry from Brigham Young University in 1941 and went on to complete his PhD in soil science at North Carolina State University in 1947. Dr. Brady then served as a member of the faculty at Cornell University in New York, USA for 26 years, rising from assistant professor to professor and chair of the agronomy department and finally to Assistant Dean of the College of Agriculture. During this period, he was elected President of both the American Society of Agronomy and of the Soil Science Society of America.

Soon after arriving at Cornell University he was recruited by Professor Harry O. Buckman to assist in co-authoring the then already classic soil science textbook, *The Nature and Properties of Soils*. The first edition of this textbook to bear Nyle Brady's name as co-author was published in 1952. Under Nyle's hand this book rose to prominence throughout the world and several generations of soil scientists got their introduction to the field through its pages. He was the sole author of editions published between 1974 in 1990. He continued to work on revised editions of this book with co-author Ray Weil until 2004. In recognition of his influence on the 15th edition, Dr. Brady continues to be listed as co-author of this textbook and his name is widely known and respected throughout the world in this capacity.

Dr. Brady was of that generation of American soil scientists that contributed so much to the original green revolution. He conducted research into the chemistry of phosphorus and the management of fertilizers and he was an early researcher on minimum tillage. Known for his active interest in international development and for his administrative skills, he was recruited in 1973 to be the third Director General of the International Rice Research Institute (IRRI) in the Philippines. Dr. Brady pioneered new cooperative relationships between IRRI and the national agricultural research institutions in many Asian countries, including a breakthrough visit to China at a time when that country was still quite closed to the outside world. He oversaw the transition to a second-generation of green revolution soil management and plant breeding designed to overcome some of the shortcomings of the first generation.

After leaving IRRI, he served as Senior Assistant Administrator for Science and Technology at the U.S. Agency for International Development from 1981 to 1989. He was a fierce champion of international scientific cooperation to promote sustainable resource use and agricultural development.

During the 1990s Dr. Brady, then in his 70s, served as senior international development consultant for the United Nations Development Programme (UNDP) and for the World Bank, in which capacity he continued to promote scientific collaboration in advances in environmental stewardship and agricultural development.

Dr. Brady was always open-minded and ready to accept new truths supported by scientific evidence, as can be seen by the evolution of the discussion of such topics as pesticide use, fertilizer management, manure utilization, tillage, soil organic matter, and soil acidity management in *The Nature and Properties of Soils* under his guidance. Nyle Brady had a larger-than-life personality, a deep sense of empathy, and an incredible understanding of how to work with people to get positive results. He was the kind of person that friends, associates, and even strangers would go to for advice when they found themselves in a perplexing position as a scientist, administrator, or even in their personal life. Dr. Brady is survived by his beloved wife, Martha, two daughters, a son (a second son preceded him in death), 22 grandchildren, and 90 great grandchildren. He will be very much missed for a long time to come by his family and by all who knew him or were touched by his work.

Preface

By opening this 15th edition of *The Nature and Properties of Soils*, you are tapping into a narrative that has been at the forefront of soil science for more than a century. The first version, published in 1909, was largely a guide to good soil management for farmers in the glaciated regions of New York State in the northeastern United States. Since then, it has evolved to provide a globally relevant framework for an integrated understanding of the diversity of soils, the soil system, and its role in the ecology of planet Earth. This latest edition is the first to feature *full color illustrations* throughout.

If you are a student reading this, you have chosen a truly auspicious time to take up the study of soil science. This new edition was completed as the United Nations and countries around the world celebrated the International Year of Soils (2015). Soils are now widely recognized as the underpinning of terrestrial ecosystems and the source of a wide range of essential ecosystem services. An understanding of the soil system is therefore critical for the success and environmental harmony of almost any human endeavor on the land. This importance of soils and soil science is increasingly recognized by business and political leaders, by the scientific community, and by those who work with the land.

Scientists and managers well versed in soil science are in short supply and becoming increasingly sought after. Much of what you learn from these pages will be of enormous practical value in equipping you to meet the many natural-resource challenges of the 21st century. You will soon find that the soil system provides many opportunities to see practical applications for principles from such sciences as biology, chemistry, physics, and geology.

This newest edition of *The Nature and Properties of Soils* strives to explain the fundamental principles of Soil Science in a manner that you will find relevant to your interests. Throughout, the text emphasizes the soil as a natural resource and soils as ecosystems. It highlights the many interactions between soils and other components of forest, range, agricultural, wetland, and constructed ecosystems. This book will serve you well, whether you expect this to be your only formal exposure to soil science or you are embarking on a comprehensive soil science education. It will provide both an exciting, accessible introduction to the world of soils and a reliable, comprehensive reference that you will want to keep for your expanding professional bookshelf.

If you are an instructor or a soil scientist, you will benefit from changes in this latest edition. Most noticeable is the use of full-color throughout which improves the new and refined figures and illustrations to help make the study of soils more efficient, engaging, and intellectually satisfying. Every chapter has been thoroughly updated with the latest advances, concepts, and applications. Hundreds of new key references have been added. This edition includes in-depth discussions on such topics of cutting edge soil science as the pedosphere concept, new insights into humus and soil carbon accumulation, subaqueous soils, soil effects on human health, principles and practice of organic farming, urban and human engineered soils, cycling and plant use of silicon, inner- and outer-sphere complexes, radioactive soil contamination, new understandings of the nitrogen cycle, cation saturation and ratios, acid sulfate soils, water-saving irrigation techniques, hydraulic redistribution, cover crop effects on soil health, soil food-web ecology, disease suppressive soils, soil microbial genomics, indicators of soil quality, soil ecosystem services, biochar, soil interactions with global climate change, digital soil maps, and many others.

In response to their popularity in recent editions, I have also added many new boxes that present either fascinating examples and applications or technical details and calculations. These boxes both *highlight* material of special interest and allow the logical thread of the regular text to flow smoothly without digression or interruption. Examples of applications boxes or case study vignettes include:

- "Dirt for Dinner"
- "Subaqueous Soils—Underwater Pedogenesis"
- "Practical Applications of Unsaturated Water Flow in Contrasting Layers"
- "Char: Is Black the New Gold?"
- "Where have All the Humics Gone?"
- "Tragedy in the Big Easy—A Levee Doomed to Fail"
- "Costly And Embarrassing Soil pH Mystery"
- "Gardeners' Friend not Always so Friendly
- "Soil Microbiology in the Molecular Age"
- "The Law of Return Made Easy: Using Human Urine"

Boxes also are provided to explain detailed calculations and practical numerical problems. Examples include:

- "Estimating CEC and Clay Mineralogy"
- "Calculating Lime Needs Based on pH Buffering"
- "Leaching Requirement for Saline Soils"
- "Calculation of Percent Pore Space in Soils"
- "Calculating Soil CEC From Lab Data"
- "Toward a Global Soil Information System"
- "Calculation of Nitrogen Mineralization"
- "Calculating a Soil-Quality Index for Plant Productivity"

As the global economy expands exponentially societies face new challenges with managing their natural resources. Soil as a fundamental natural resource is critical to sustained economic growth and the prosperity of people in all parts of the world. To achieve balanced growth with a sustainable economy while improving environmental quality, it will be necessary to have a deep understanding of soils, including their properties, functions, ecological roles, and management. I have written this textbook in a way designed to engage inquisitive minds and challenge them to understand soils and actively do their part as environmental and agricultural scientists, in the interest of ensuring a prosperous and healthy future for humanity on planet Earth.

This understanding must include the role of healthy soils in agricultural applications and the pressing need for increasing food production. However, it must also include knowledge of the many other ecosystem services provided by soils. In this textbook I have tried to take a broad view of soils in the environment and in relation to human society. In so doing, the book focuses on six major ecological roles of soil. Soils provide for the growth of plants, which, in turn, provide wildlife habitat, food for people and animals, bio-energy, clothing, pharmaceuticals, and building materials. In addition to plant production, soils also dramatically influence the Earth's atmosphere and therefore the direction of future climate change. Soils serve a recycling function that, if taken advantage of, can help societies to conserve and reuse valuable and finite resources. Soils harbor a large proportion of the Earth's biodiversity—a resource which modern technology has allowed us to harness for any number of purposes. Water, like soil, will be a critical resource for the future generations. Soils functions largely determine both the amount of water that is supplied for various uses and also the quality and purification of that water. Finally, knowledge of soil physical properties and behavior, as well as an understanding of how different soils relate to each other in the landscape, will be critical for successful and sustainable engineering projects aimed at effective and safe land development.

For all these reasons it will be essential for the next generation of scientists, business people, teachers, and other professionals to learn enough about soils to appreciate their importance and to take them into full consideration for development projects and all activities on the land. It is my sincere hope that this book, early editions of which have served so many generations of soil students and scientists, will allow new generations of future soil scientists to benefit from the global ecological view of soils that this textbook expounds.

Dr. Nyle Brady, although long in retirement and recently deceased, remains as co-author in recognition of the fact that his vision, wisdom, and inspiration continue to permeate the entire book. Although the responsibility for writing the 15th edition was solely mine, I certainly could not have made all of the many improvements without innumerable suggestions, ideas, and corrections contributed by soil scientists, instructors, and students from around the world. The 15th edition, like preceding editions, has greatly benefited from the high level of professional devotion and camaraderie that characterizes the global soil science community.

Special thanks go to Dr. Rachel Gilker for her invaluable editorial and research assistance. I also thank the following colleagues (listed alphabetically by institution) for their especially valuable suggestions, contributions, reviews, and inspiration: Pichu Rengasamy (The University of Adelaide); Michéli Erika (Univ. Agricultural Science, Hungary); Duane Wolf (University of Arkansas); Tom Pigford (University of California, Berkeley); Thomas Ruehr (Cal Poly State University); J. Kenneth Torrence (Carleton University); Pedro Sanchez and Cheryl Palm (Columbia University); Harold van Es and Johannes Lehmann (Cornell University); Eric Brevik (Dickinson State University); Dan Richter (Duke University); Owen Plank (University of Georgia); Robert Darmody, Laura Flint Gentry, Colin Thorn, and Michelle Wander (University of Illinois); Roland Buresh (International Rice Research Institute); Lee Burras (Iowa State University); Aurore Kaisermann (Laboratoire Bioemco); Daniel Hillel (University of Massachusetts, Emeritus); Lyle Nelson (Mississippi State University, Emeritus); Jimmie Richardson (North Dakota State University); Rafiq Islam and Rattan Lal (The Ohio State University); David Munn (Ohio State ATI); Darrell Schultze (Purdue University); Joel Gruver (Western Illinois University); Ivan Fernandez (University of Maine); David Lobb (University of Manitoba); Mark Carroll, Glade Dlott, Delvin Fanning, Nicole Fiorellino, Robert Hill, Bruce James, Natalie Lounsbury, Brian Needelman, Martin Rabenhorst, Patricia Steinhilber, and Stephane Yarwood (University of Maryland); Martha Mamo (University of Nebraska); Jose Amador (University of Rhode Island); Russell Briggs (State University of New York); Allen Franzluebbers, Jeff Herrick, Scott Lesch, and Jim Rhoades (USDA/Agricultural Research Service); Bob Ahrens, Bob Engel, Maxine Levine, Paul Reich, Randy Riddle, Kenneth Scheffe, and Sharon Waltman (USDA/Natural Resources Conservation Service); Markus Kleber (Oregon State University); Henry Lin (The Pennsylvania State University); Joseph Heckman (Rutgers, The State University of New Jersey); Fred Magdoff and Wendy Sue Harper (University of Vermont); W. Lee Daniels, John Galbraith (Virginia Tech); Peter Abrahams (University of Wales); Luther Carter (Washington, DC); Clay Robinson (West Texas A & M University); Tor-G. Vagen (World Agroforestry Center); Larry Munn (University of Wyoming); and Tom Siccama (Yale University).

Last, but not least, I deeply appreciate the good humor, forbearance, and patience of my wife, Trish, and those students and colleagues who may have felt some degree of neglect as I focused so much of my energy, time, and attention on this labor of love.

RRW
College Park, Maryland, USA
February 2016

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Earth, our unique soil- and water-covered planet. (NASA)

1 The Soils Around Us

For in the end we will conserve only what we love.
We will love only what we understand.
And we will understand only what we are taught.
—*Baba Dioum*, African Conservationist

The Earth, our only home in the vastness of the universe, is unique for living systems sustained by its air, water, and soil resources. Among the millions of life forms on our planet, one species, the human species, has become so dominant that the quality of those resources now depends on that species learning to exercise a whole new level of stewardship.

Human activities are changing the very nature of the Earth's ecology. Some 50% of the land surface has been appropriated for human use. Depletion of stratospheric ozone is threatening to overload us with ultraviolet radiation. Emissions of carbon dioxide, nitrogen oxides, and methane gases are warming the planet and destabilizing the global climate. Tropical rain forests, and their incredible array of plants and animals, are disappearing at an unprecedented rate. Groundwater supplies are being contaminated and depleted. In parts of the world, the capacity of soils to produce food is being degraded, even as the number of people needing food is increasing. Bringing the global environment back into balance may well be the defining challenge for the current generation of students studying soils.

Soils[1] are crucial to life on Earth. To a great degree, the quality of the soil present determines the nature of plant ecosystems and the capacity of land to support animal life and society. Soils also play a central role in many of today's environmental challenges. From water pollution and climate change to biodiversity loss and human food supply, the world's ecosystems are impacted in far-reaching ways by processes carried out in the soil. As human societies become increasingly urbanized, fewer people have intimate contact with the soil, and individuals tend to lose sight of the many ways in which they depend upon soils for their prosperity and survival. Indeed, the degree to which we are dependent on soils is likely to increase, not decrease, in the future.

Soils will continue to supply us with nearly all of our food, yet how many of us remember, as we eat a slice of pizza, that the pizza's crust began in a field of wheat and its cheese began with grass, clover, and corn rooted in the soils of a dairy farm? Most of the fiber we use for lumber, paper, and clothing has its roots in the soils of forests and farmland. Although we sometimes use plastics and fiber synthesized from fossil petroleum as substitutes, in the long term we will continue to depend on terrestrial ecosystems for these needs.

In addition, biomass grown on soils is likely to become an increasingly important feedstock for fuels and manufacturing as the world's finite supplies of petroleum are depleted during the course of this century. The early marketplace signs of this trend can be

[1]Throughout this text, bold type indicates key terms whose definitions can be found in the glossary.

Figure 1.1 *Environmental and economic imperatives suggest that we will become more dependent on soil to produce renewable materials that can substitute for increasingly scarce and environmentally damaging nonrenewables. Biodiesel fuel* (left) *produced from soybean and other oil crops is far less polluting and has less impact on global warming than petroleum-based diesel fuel. Other oil crops can substitute for petroleum to produce nontoxic inks* (bottom), *plastics, and other products. Cornstarch can be made into biodegradable plastics for such products as plastic bags and foam-packing "peanuts"* (upper right). (Photos courtesy of Ray R. Weil)

seen in the form of ethanol and biodegradable plastics synthesized from corn or biodiesel fuels and printers' inks made from soybean oil (Figure 1.1).

One of the stark realities of the 21st century is that the population of humans that demands all of these products will increase by several billion (population is expected to stabilize later this century at 9 to 10 billion). Unfortunately, the amount of soil available to meet these demands will not increase at all. In fact, the resource base is actually *shrinking* because of soil degradation and urbanization. Understanding how to better manage the soil resource is essential to our survival and to the maintenance of sufficient habitat for the other creatures that share this planet with us. In short, the study of soil science has never been more important than it is today.

1.1 WHAT ECOSYSTEM SERVICES DO SOILS PERFORM?

Scientists now recognize that the world's ecosystems provide goods and services estimated to be worth tens of trillions of dollars every year—as much as the gross national products (GNP) of all the world's economies (see Section 20.3). **Ecosystem services** can be thought of as:

- *provisioning* (providing goods such as water, food, medicines, lumber, etc.),
- *regulating* (processes that purify water, decompose wastes, control pests, or modify atmospheric gases),
- *supportive* (assisting with nutrient cycling, seed dispersal, primary biomass production, etc.) and
- *cultural* (providing spiritual uplift, scenic views, and outdoor recreation opportunities).

Over half of global ecosystem services arise on land, where soils play a major role.

Whether occurring in your backyard, a farm, a forest, or a regional watershed, soils have six key roles to play (Figure 1.2) in the provision of ecosystem services. *First*, soils support plant growth, by providing habitat for plant roots and nutrient elements for the entire plant. Soil properties often determine the nature of the vegetation present and, indirectly, the number and types of animals (including people) that the vegetation can support. *Second*, soils regulate water supplies. Water loss, utilization, contamination, and purification are all affected by

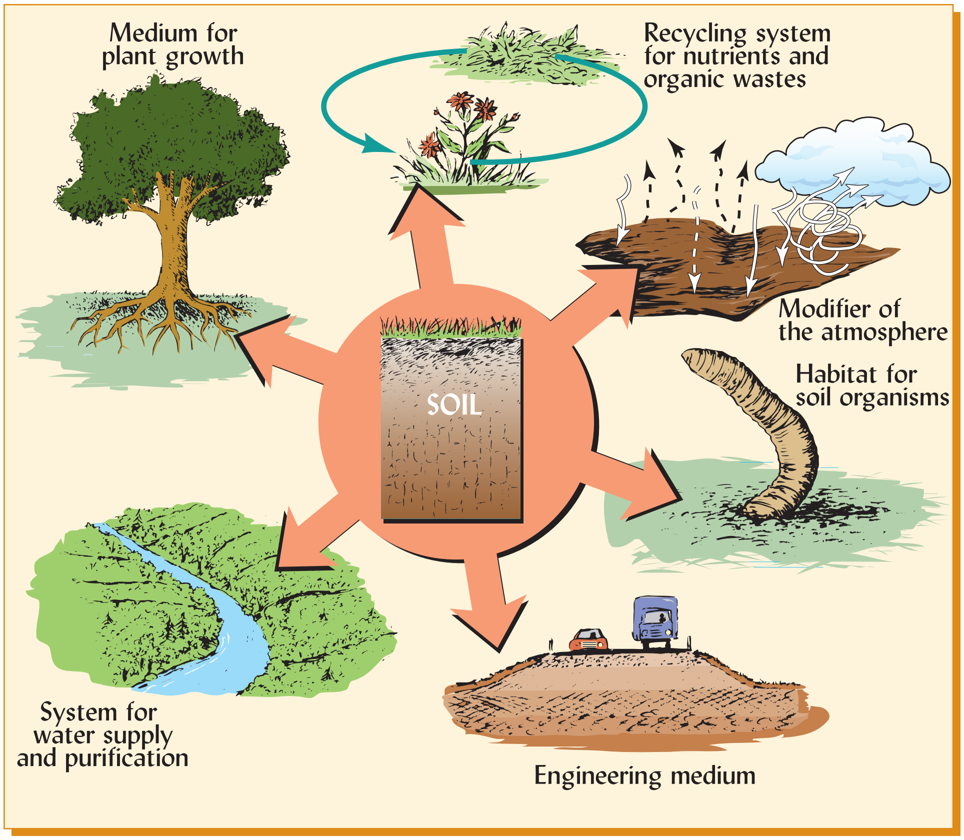

Figure 1.2 *The many functions and ecosystem services performed by soil can be grouped into six crucial ecological roles.* (Diagram courtesy of Ray R. Weil)

the soil. *Third*, the soil functions as nature's recycling system. Within the soil, waste products and dead bodies of plants, animals, and people are assimilated, and their basic elements are made available for reuse by the next generation of life. In addition to recycling, soil can serve as a protective covering of human artifacts for centuries before they are unearthed by archeologists. *Fourth*, soils are alive and are home to creatures from small mammals and reptiles to tiny insects to microorganisms of unimaginable numbers and diversity. *Fifth*, soils markedly influence the composition and physical condition of the atmosphere by taking up and releasing large quantities of carbon dioxide, oxygen, and other gases and by contributing dust and re-radiated heat energy to the air. *Finally*, soil plays an important role as an engineering medium. Soil is not only an important building material in the form of earth fill and bricks (baked soil material) but provides the foundation for virtually every road, airport, and house we build.

1.2 HOW DO SOILS SUPPORT PLANT GROWTH?

When we think of the forests, prairies, gardens, and fields that surround us, we usually envision the **shoots**—the plant leaves, flowers, stems, and limbs—forgetting that half of the plant world, the **roots**, exists belowground. Because plant roots are usually hidden from our view and difficult to study, we know much less about plant—environment interactions belowground than aboveground, but we must understand both to truly understand either. To begin with, let's list and then briefly discuss what a plant obtains from the soil in which its roots proliferate:

- Physical support
- Air
- Water
- Temperature moderation
- Protection from toxins
- Nutrient elements

First, the soil mass provides physical support, anchoring the root system so that the plant does not fall over or blow away. Occasionally, strong wind or heavy snow does topple a plant whose root system has been restricted by shallow or inhospitable soil conditions (Figure 1.3).

Figure 1.3 *This wet, shallow soil failed to allow sufficiently deep roots to develop to prevent this tree from blowing over when snow-laden branches made it top-heavy during a winter storm.* (Photo courtesy of Ray R. Weil)

Because root respiration, like our own respiration, produces carbon dioxide (CO_2) and uses oxygen (O_2), an important function of the soil is ***ventilation***—maintaining the quantity and quality of air by allowing CO_2 to escape and fresh O_2 to enter the root zone. This ventilation is accomplished via networks of soil pores.

An equally important function of soil pores is to absorb water and hold it where it can be used by plant roots. As long as plant leaves are exposed to sunlight, the plant requires a continuous stream of water to use in cooling, nutrient transport, turgor maintenance, and photosynthesis. Since plants use water continuously, but in most places it rains only occasionally, the water-holding capacity of soils is essential for plant survival. A deep soil may store enough water to allow plants to survive long periods without rain (Figure 1.4).

The soil also moderates temperature fluctuations. Perhaps you can recall digging in garden soil (or even beach sand) on a summer afternoon and feeling how hot the soil was at the surface and how much cooler just a few centimeters below. The insulating properties of soil protect the deeper portion of the root system from extremes of hot and cold that often occur at

Figure 1.4 *A family of African elephants finds welcome shade under the leafy canopy of a huge acacia tree in this East African savanna. The photo was taken in a long dry season; no rain had fallen for almost five months. The tree roots are still using water from the previous rainy season stored several meters deep in the soil. The light-colored grasses are more shallow-rooted and have either set seed and died or gone into a dried-up, dormant condition.* (Photo courtesy of Ray R. Weil)

the soil surface. For example, it is not unusual for the mid-afternoon temperature at the surface of bare soil to reach 40 °C, a condition lethal to most plant roots. Just a few centimeters deeper, however, the temperature may be 10 °C cooler, allowing roots to function normally.

Phytotoxic substances in soils may result from human activity (such as chemical spills or herbicide application), or they may be produced by plant roots, by microorganisms, or by natural chemical reactions. Many soil managers consider it a function of a good soil to protect plants from such substances by ventilating gases, by decomposing or adsorbing organic toxins, or by suppressing toxin-producing organisms. At the same time, it is true that some microorganisms in soil produce organic, growth-stimulating compounds. These substances, when taken up by plants in small amounts, may improve plant vigor.

A fertile soil will provide a continuing supply of dissolved **mineral nutrients** in amounts and relative proportions appropriate for optimal plant growth. These nutrients include such metallic elements as potassium, calcium, iron, and copper, as well as such nonmetallic elements as nitrogen, sulfur, phosphorus, and boron. Roots take these elements out of the soil solution and the plant incorporates most of them into the organic compounds that constitute its tissues. Animals usually obtain their mineral nutrients from the soil, indirectly, by eating plants. Under some circumstances, animals (including humans) satisfy their craving for minerals by ingesting soil directly (Figure 1.5 and Box 1.1). Plants also take up some elements that they do not appear to use, which is fortunate as animals do require several elements that plants do not (see periodic table, Appendix B).

Of the 92 naturally occurring chemical elements, 17 have been shown to be **essential elements**, meaning that plants cannot grow and complete their life cycles without them. Table 1.1 lists these and several additional elements that appear to be quasi-essential (needed by some but not all plants). Essential elements used by plants in relatively large amounts are called **macronutrients**; those used in smaller amounts are known as **micronutrients**. To remember the 17 essential elements, try this mnemonic device:

C.B. HOPKiNS CaFé—
__Cl__osed __Mo__nday __Mo__rning and __Ni__ght—
See You Zoon,** the* ***Mg

The bold letters indicate the chemical elements in this phrase; finding copper (Cu) and zinc (Zn) may require a bit of imagination.

In addition to the mineral nutrients just listed, plants may also use minute quantities of organic compounds from soils. However, uptake of these substances is not necessary for normal plant growth. The organic metabolites, enzymes, and structural compounds making up a plant's dry matter consist mainly of carbon, hydrogen, and oxygen, which the plant obtains by photosynthesis from air and water, not from the soil.

Plants *can* be grown in nutrient solutions without any soil (a method termed **hydroponics**), but then the plant-support functions of soils must be engineered into the system and maintained at a high cost of time, energy, and management. In fact, imagining the expense of attempting to grow enough for 7 billion people in hydroponic greenhouses is a

Figure 1.5 *A mountain goat (in Glacier National Park, USA) visits a natural* salt lick *where it ingests needed minerals directly from the soil. Animals normally obtain their dietary minerals indirectly from soils by eating plants.* (Photo courtesy of Ray R. Weil)

BOX 1.1

DIRT FOR DINNER?[a]

You are probably thinking, "dirt (excuse me, *soil*) for dinner? Yuck!" Of course, various birds, reptiles, and mammals are well known to consume soil at special "licks," and involuntary, inadvertent ingestion of soil by humans (especially children) is widely recognized as a pathway for exposure to environmental toxins (see Chapter 18, Box 18.2), but many people, anthropologists and nutritionists included, find it hard to believe that anyone would *purposefully* ingest soil. Yet, research on the subject shows that many people do routinely eat soil, often in amounts of 20 to 100 g (up to $^1/_4$ pound) daily. **Geophagy** (deliberate "soil eating") is practiced in societies as disparate as those in Thailand, Turkey, rural Alabama, and urban Tanzania (Figure 1.6). Immigrants have brought the practice of soil eating to such cities as London and New York. In fact, scientists studying the practice suggest that geophagy is a widespread and normal human behavior. Children and women (especially when pregnant) appear more likely than men to be geophagists. Poor people eat soil more commonly than the relatively well-to-do.

People usually do not eat just any soil, but seek out particular soils, generally high in clay and low in sand, be it the hardened clay of a termite nest, the soft, white clay exposed in a riverbank, or the dark red clay from a certain deep soil layer. People in different places and circumstances seek to consume different types of soils—some seek sodium- or calcium-rich soils, others soil with high amounts of certain clays, still others seek soils rich in iron. Interestingly, unlike many other animals, humans rarely appear to eat soil to obtain salt. Possible benefits from eating soil may include mineral nutrient supplementation, although only iron appears to be sufficiently bioavailable to actually improve nutrition. While other mammals seem to obtain significant amounts of mineral nutrients from eating soil, the main benefit that humans receive is probably detoxification of ingested poisons and parasites (e.g., by adsorption to clay—see Chapter 8), relief from stomachaches, survival in times of famine, and psychological comfort. Geophagists have been known to go to great lengths to satisfy their cravings for soil. But before you run out and add some local soil to your menu, consider the potential downsides to geophagy. Aside from the possibly difficult task of developing a taste for the stuff, the drawbacks to eating soil (especially surface soils) can include parasitic worm infection, lead poisoning, and mineral nutrient imbalances (because of adsorption of some mineral nutrients and release of others)—as well as premature tooth wear!

Figure 1.6 *Bars of reddish clay soil sold for human consumption in a market in Morogoro, Tanzania. The soil bars (stacked neatly on the circular tray in foreground) are sold individually or by the bagful mainly to pregnant women, who commonly consume about 10 bars per day.* (Photo courtesy of Ray R. Weil)

[a]This box is largely based on a fascinating reviews by Young et al. (2011) and Abrahams (2012), (2005).

Table 1.1
Elements Needed for Plant Growth and Their Sources[a]

The chemical forms most commonly taken in by plants are shown in parentheses, with the chemical symbol for the element in bold type.

Macronutrients: Used in relatively large amounts (>0.1% of dry plant tissue)		Micronutrients: Used in relatively small amounts (<0.1% of dry plant tissue)
Mostly from air and water	**Mostly from soil solids**	**From soil solids**
Carbon ($\mathbf{C}O_2$)	*Cations:*	*Cations:*
Hydrogen ($\mathbf{H}_2O$)	Calcium ($\mathbf{Ca}^{2+}$)	Copper ($\mathbf{Cu}^{2+}$)
Oxygen ($\mathbf{O}_2$, $H_2\mathbf{O}$)	Magnesium ($\mathbf{Mg}^{2+}$)	*Cobalt ($\mathbf{Co}^{2+}$)[b]
	Nitrogen ($\mathbf{N}H_4^+$)	Iron ($\mathbf{Fe}^{2+}$)
	Potassium ($\mathbf{K}^+$)	Manganese ($\mathbf{Mn}^{2+}$)
	Anions:	Nickel ($\mathbf{Ni}^{2+}$)
	Nitrogen ($\mathbf{N}O_3^-$)	*Sodium ($\mathbf{Na}^+$)[b]
	Phosphorus ($H_2\mathbf{P}O_4^-$, $H\mathbf{P}O_4^{2-}$)	Zinc ($\mathbf{Zn}^{2+}$)
	Sulfur ($\mathbf{S}O_4^{2-}$)	*Anions:*
	*Silicon ($H_4\mathbf{Si}O_4$, $H_3\mathbf{Si}O_4^-$)[b]	Boron ($H_3\mathbf{B}O_3$, $H_4\mathbf{B}O_4^-$)
		Chlorine ($\mathbf{Cl}^-$)
		Molybdenum ($\mathbf{Mo}O_4^{2-}$)

[a]Many other elements are taken up from soils by plants but are not *essential* for plant growth. Some of these (such as iodine, fluorine, barium, and strontium) do enhance the growth of certain plants, but do not appear to be absolutely required for normal growth, as are the 20 listed in this table. Still other elements (e.g., chromium, selenium, tin, and vanadium) are incorporated into plant tissues, where they may be used as essential mineral nutrients by humans and other animals, even though plants do not appear to require them. See periodic table in Appendix B.

[b]Elements marked by (*) are quasi-essential elements (*sensu*, Epstein and Bloom (2005)), required for some, but not for all, plants. Silicon is used in large amounts to play important roles in most plants, so is considered a plant-beneficial element, but has been proved essential only for diatoms and plants in the *Equisetaceae* family. Cobalt has been proved essential for only *Leguminosae* when in symbiosis with nitrogen-fixing bacteria (see Section 13.10). Sodium is essential in small amounts for plants using the C_4 photosynthesis pathway (mainly tropical grasses).

good way to comprehend the economic value of the food provision ecosystem service provided by soils. Thus, although hydroponic production is feasible for high-value plants on a small scale, production of the world's food and fiber and maintenance of natural ecosystems will always depend on millions of square kilometers of productive soils.

1.3 HOW DO SOILS REGULATE WATER SUPPLIES?

There is much concern about the quality and quantity of the water in our rivers, lakes, and underground aquifers. To maintain or improve water quality, we must recognize that nearly every drop of water in our rivers, lakes, estuaries, and aquifers has either traveled through the soil or flowed over its surface (excluding the relatively minor quantity of precipitation that falls directly into bodies of fresh surface water). Imagine, for example, a heavy rain falling on the hills surrounding the river in Figure 1.7. If the soil allows the rain to soak in, some of the water will be stored in the soil, some used by the trees, and some will seep slowly down through the soil layers to the groundwater, eventually entering the river over a period of months or years as **base flow**. As it soaks through the upper layers of soil, contaminated water is purified and cleansed by soil processes that remove many impurities and kill potential disease organisms.

Contrast the preceding scenario with what would occur if the soil were so shallow or impermeable that most of the rain could not penetrate the soil, but ran off the land surface, scouring surface soil and debris as it sped toward the river. The result would be a destructive flash flood of muddy contaminated water. This comparison highlights how the nature and

Figure 1.7 *The condition of the soils covering these Blue Ridge foothills will greatly influence the quantity and quality of water flowing down the James River in Virginia, USA.* (Photo courtesy of Ray R. Weil)

management of soils in a watershed will influence the purity and amount of water finding its way to aquatic systems. For those who live in rural homes, the purifying action of the soil (in a septic drain field as described in Section 6.8) is the main barrier that stands between what flushes down the toilet and the water running into the kitchen sink!

1.4 HOW DO SOILS RECYCLE RAW MATERIALS?

What would a world be like without the recycling functions performed by soils? Without reuse of nutrients, plants and animals would have run out of nourishment long ago. The world would be covered with a layer, possibly hundreds of meters high, of plant and animal wastes and corpses. Obviously, recycling is vital to ecosystems, whether forests, farms, or cities. The soil system plays a pivotal role in the major geochemical cycles. Soils have the capacity to assimilate great quantities of organic waste, turning it into beneficial **soil organic matter**, converting the mineral nutrients in the waste to forms that can be utilized by plants and animals, and returning the carbon to the atmosphere as carbon dioxide, where it again will become a part of living organisms through plant photosynthesis. Some soils can accumulate large amounts of carbon as soil organic matter, thus reducing the concentration of atmospheric carbon dioxide and potentially mitigating global climate change (see Sections 1.5, 1.14, and 12.2).

1.5 HOW DO SOILS MODIFY THE ATMOSPHERE?

As the soil "breathes" in and out it interacts in many ways with the Earth's blanket of air. That is, soils absorb oxygen and other gases such as methane, while they release gases such as carbon dioxide and nitrous oxide. These gas exchanges between the soil and the atmosphere have a significant influence on atmospheric composition and global climate change. The evaporation of soil moisture is a major source of water vapor in the atmosphere, altering air temperature, composition, and weather patterns.

In places where the soil is dry, poorly structured, and unvegetated, soil particles can be picked up by winds and contribute great quantities of dust to the atmosphere, reducing visibility, increasing human health hazards from breathing dirty air, and altering the temperature of the air and of the Earth itself. Moist, well-vegetated, and structured soils can prevent such dust-laden air.

1.6 WHAT LIVES IN THE SOIL HABITAT?

When speaking of ecosystems needing protection, most people envision a stand of old-growth forest with its abundant wildlife, or an estuary with oyster beds and fisheries. Perhaps, once you have read this book, you will envision a handful of soil when someone speaks of an ecosystem.

Figure 1.8 *The soil is home to a wide variety of organisms, both relatively large and very small. Here, a relatively large predator, a centipede (shown at about actual size), hunts for its next meal—which is likely to be one of the many smaller animals that feed on dead plant debris.* (Photo courtesy of Ray R. Weil)

Soil is not a mere pile of broken rock and dead debris. A handful of soil may be home to *billions* of organisms, belonging to thousands of species that act as predators, prey, producers, consumers, and parasites (Figure 1.8). This complex community of organisms influences human well-being through many ecosystem functions, but soils also influence human health directly, for good or for ill (see Box 1.2)

BOX 1.2

SOILS AND HUMAN HEALTH[a]

Although human health impacts of soils often go unrecognized, they affect us all for better and for worse. Soils impact our health indirectly via all six of the ecological soil functions described in Sections 1.2–1.7. Soils and soil components (such soil particles, mineral elements, and microorganisms) also directly affect our health when we come in contact with them by handling soil or in the food we eat, the water we drink, and the air we breathe.

THE FOOD WE EAT

The composition of our food reflects the nature of the soil in which it was grown. Zinc, which is involved in the function of hundreds of our body's enzymes, is a case in point; with insufficient dietary intake we may suffer such symptoms as hair loss and impairment of immune system function, fertility, and sex drive. About half of the world's agricultural soils are deficient in zinc, and about half of the world's people (largely in the same geographic areas) eat diets deficient in this micronutrient. Likewise, soils low in sulfur, as occur widely in Africa, Asia, Australia, and parts of North America, produce wheat (or beans, etc.) likely to be low in methionine and cystine, sulfur-containing amino acids essential for the human body to utilize the protein in food. Foods grown in certain areas tend to reflect the low levels of iodine and selenium in local soils, two elements not needed by plants but widely deficient as nutrients for people (causing goiters and Keshan disease, respectively). Other examples abound.

INFECTIOUS DISEASES FROM SOILS

Among the millions of soil-dwelling organisms, a few can bring disease and even death to humans. Among the more notorious soil pathogenic bacteria are *Clostridium tetani*, which causes tetanus and *Bacillus anthracis*, which causes anthrax and whose spores may survive in the soil for decades. Such soil-borne infectious bacterial diseases kill millions of people each year, including many babies and mothers who die during childbirth under unsanitary conditions. A less common, but still potentially fatal, soil-borne disease is caused when a soil fungus, *Blastomyces sp*, infects a cut in the skin or is breathed into the lungs. Blastomycosis is usually associated geographically with localized soil conditions, but it is hard to track down as its pneumonia-like lung symptoms or skin ulcerations may not appear for months after exposure. Cryptococcosis, a fairly rare disease causing brain damage or pneumonia-like lung symptoms, can be contracted by breathing in spores of *Cryptococcus*, another soil fungus. Still other human diseases are caused by microscopic soil animals, such round worms, hook worms, and

[a]Many scientific papers are available for further reading on soils and human health [see Alloway and Graham (2008); Frager et al. (2010); Griffin (2007); Liu and Khosla (2010); Stokes (2006)]. For research that illuminates why soil clays exhibit powers of healing (it's the metals adsorbed to the clays!), see Otto and Haydel (2013). For a review of human immune system regulation by soil (and other environmental) organisms, see Rook (2013).

(continued)

BOX 1.2

SOILS AND HUMAN HEALTH *(CONTINUED)*

protozoa. An example of the latter is *Cryptosporidium sp.*, which cause widespread outbreaks of cryptosporidiosis, sometimes sickening (but rarely killing) thousands of people in a single city if the protozoa-containing soil or farm manure contaminates drinking water supplies. Another under-recognized health hazard comes from fine dust picked up by desert winds and carried halfway around the world (see Sections 2.2 and 17.2). Airborne dust not only poses a risk of physical irritation of lung tissues that results in cancer, but also carries pathogenic soil microorganisms that can remain alive and virulent during the intercontinental journey.

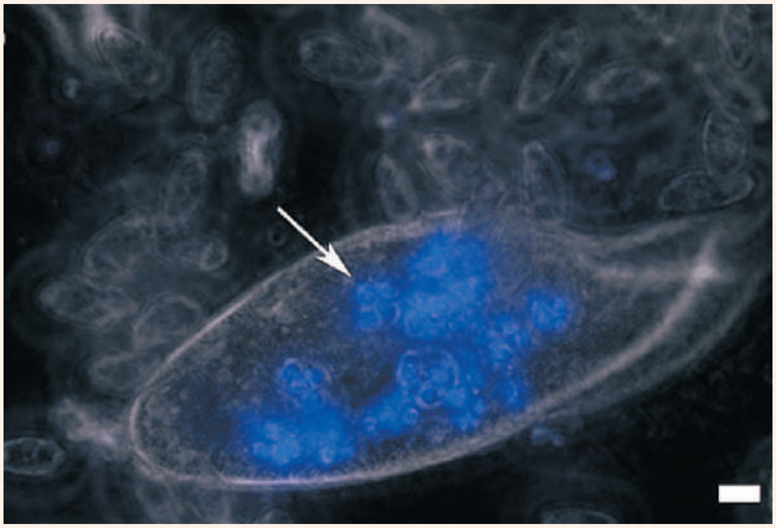

Figure 1.9 *Balance of nature in the soil ecosystem. This Paramecium, a single celled soil animal (protista) ingests and kills spores of the human pathogenic fungus Cryptococcus. Arrow shows spores inside the paramecium; white scale bar = 1μm. Microscopic image from Frager et al. (2010).*

THE CURATIVE POWERS OF SOILS

The aforementioned discussion does not mean that we should never hike in the forest or garden without rubber gloves (though gloves are a good idea if your hand has an open wound). To the contrary—the balance of nature in most soils is overwhelmingly in favor of organisms that provide ecosystem services essential to human welfare. For example, it was recently observed (Figure 1.9) that certain single-celled soil animals called *Paramecium*, voraciously eat the spores of the pathogenic fungus *Cryptococcus* just mentioned. In fact, soils play a far greater role in *curing* our diseases than in *causing* them!

Many people are unaware that plants grown in the soil are the source of most of the medicines (both traditional herbals and modern pharmaceuticals) that prevent, alleviate or cure so many of the diseases and ailments that plagued and often killed our ancestors. The story of Taxol (paclitaxel) illustrates this role quite well. This highly prized anticancer drug was first discovered in the bark of a rare type of yew tree that grows in the Pacific coast soils of Oregon and Washington States. Demand for this drug resulted in the destruction of half a million of these yews before scientists learned to make it from other organisms using molecular culture and gene-transfer techniques.

Soil microorganisms themselves are the source of most of our life-saving antibiotics Drugs such as penicillin, ciprofloxacin, and neomycin originate from certain soil bacteria (e.g., *Streptomyces*) and fungi (e.g., *Penicillium*) that produce these compounds as part of their defensive strategies against competing soil microbes. See Chapter 11 for more on soil microbes and their antibiotics. Poultices made from soil clays have long been effectively used in traditional medicine to heal skin conditions and fight infections. Some research even suggests that just being in close contact with healthy soils (think avid gardeners) and breathing in certain microorganisms or volatile compounds they produce may give people a sense of well-being through interactions with their brain chemistry (the marked increase in brain cell serotonin in response to the soil bacterium, *Mycobacterium vaccae*, is well documented). Regulation of our immune systems and promotion of our well-being by diverse soil microbes should be considered among the ecosystem services that soils provide.

We have said that billions of organisms made up of thousands of species can coexist in a handful of soil. How is it possible for such a diversity of organisms to live and interact in such a small space? One explanation is the tremendous range of niches and habitats that exist in even a uniform-appearing soil. Some pores of the soil will be filled with water in which organisms such as roundworms, diatoms, rotifers, and bacteria swim. Tiny insects and mites may be crawling about in other larger pores filled with moist air. Micro-zones of good aeration may be only millimeters from areas of **anoxic** conditions. Different areas may be enriched with decaying organic materials; some places may be highly acidic, some more basic. Temperature, too, may vary widely.

Hidden from view in the world's soils are communities of living organisms every bit as complex and intrinsically valuable as their larger counterparts that roam the savannas, forests, and oceans of the Earth. In fact, soils harbor a large part of the Earth's genetic diversity. Soils, like air and water, are important components of larger ecosystems. So it is important to assure that **soil quality** is considered, along with air quality and water quality, in discussions of environmental protection.

1.7 SOIL AS AN ENGINEERING MEDIUM

Soil is one of the earliest and the most widely used of building materials. Nearly half the people in the world live in houses constructed from soil. Soil buildings vary from traditional African mud huts to large centuries-old circular apartment houses in China (Figure 1.10) to today's environmentally-friendly "rammed-earth" buildings (see http://www.yourhome.gov.au/materials/rammed-earth).

"*Terra firma*, solid ground." We usually think of the soil as being firm and solid, a good base on which to build roads and all kinds of structures. Indeed, most constructed structures do rest on the soil, and many construction projects require excavation into the soil. Unfortunately, as can be seen in Figure 1.11, some soils are not as stable as others. Reliable construction on soils, and with soil materials, requires knowledge of the diversity of soil properties, as discussed in this and later chapters. Designs for roadbeds or building foundations that work well in one location on one type of soil may be inappropriate for another location with different soils.

Working with natural soils or excavated soil materials is not like working with concrete or steel. Properties such as bearing strength, compressibility, shear strength, and stability are much more variable and difficult to predict for soils than for manufactured building materials. Chapter 4 provides an introduction to some engineering properties of soils. Many other physical properties discussed will have direct application to engineering uses of soil. For example, Chapter 8 discusses properties of certain types of clay soils that upon wetting expand with sufficient force to crack foundations and buckle pavements. Much of the information on soil properties and soil classification discussed in later chapters will be of great value to people planning land uses that involve construction or excavation.

Figure 1.10 *Soil is among the oldest and most common of building materials, with half the world's people living in homes made of soil.* (left) *An elderly African villager weaves a basket outside his house made from red and black clay soil reinforced with small tree branches (a technique termed wattle and daub).* (right) *Several round* Tulou *apartment buildings housing up to 80 families each in Fu-Jian, China. These buildings have 2-m-thick walls made thousands of years ago from compacted yellowish soil mixed with bamboo and stones. These massive "rammed earth" walls make the buildings warm in winter but cool in summer (see Chapter 7) and resistant to damage from earthquakes.* (Left photo courtesy of Ray R. Weil; right photo courtesy of Lu Zhang, Zhejiang, China)

Figure 1.11 *Better knowledge of the soils on which this road was built may have allowed its engineers to develop a more stable design, thus avoiding this costly and dangerous situation.* (Photo courtesy of Ray R. Weil)

1.8 THE PEDOSPHERE AND THE CRITICAL ZONE?[2]

The outer layers of our planet that lie between the tops of the tallest trees and the bottom of the groundwater aquifers that feed our rivers comprise what scientists term ***The Critical Zone***. Environmental research is increasingly focused on this zone where active cycles and flows of materials and energy support life on Earth. The soil plays a central role in this critical zone. The importance of the soil derives in large part from its role as an **interface** between the worlds of rock (the **lithosphere**), air (the **atmosphere**), water (the **hydrosphere**), and living things (the **biosphere**). Environments where all four of these worlds interact are often the most complex and productive on Earth. An estuary, where shallow waters meet the land and air, is an example of such an environment. The soil, or **pedosphere**, is another example (Figure 1.12).

The concept of the soil as interface means different things at different scales. At the scale of kilometers (Figure 1.12*a*), soils channel water from rain to rivers and transfer mineral elements from bed rocks to the oceans. They also substantially influence the global balance of atmospheric gases. At a scale of a few meters (Figure 1.12*b*), soil forms the transition zone between hard rock and air, holding both liquid water and oxygen gas for use by plant roots. It transfers mineral elements from the Earth's rock crust to its vegetation. It processes or stores the organic remains of terrestrial plants and animals. At a scale of a few millimeters (Figure 1.12*c*), soil provides diverse micro-habitats for air-breathing and aquatic organisms, channels water and nutrients to plant roots, and provides surfaces and solution vessels for thousands of biochemical reactions. Finally, at the scale of a few micrometers or nanometers (Figure 1.12*d*), soil provides ordered and complex surfaces, both mineral and organic, that act as templates for chemical reactions and interact with water and solutes. Its tiniest mineral particles form micro-zones of electromagnetic charge that attract everything from bacterial cell walls to proteins to conglomerates of water molecules. As you read the entirety of this book, the frequent cross-referencing between one chapter and another will remind you of the importance of scale and interfacing to the story of soil.

1.9 SOILS AS NATURAL BODIES

You may notice that this book sometimes refers to "soil," sometimes to "the soil," sometimes to "a soil," and sometimes to "soils." These variations of the word "soil" refer to two distinct concepts—*soil* as a material or *soils* as natural bodies. *Soil* is a material composed of minerals, gases, water, organic substances, and microorganisms. Some people (usually *not* soil scientists!)

[2]For a readable introduction to the concept of the Critical Zone, see Fisher (2012).