NYLE C. BRADY
RAY R. WEIL

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ELEMENTS OF THE NATURE AND PROPERTIES OF SOILS

THIRD EDITION

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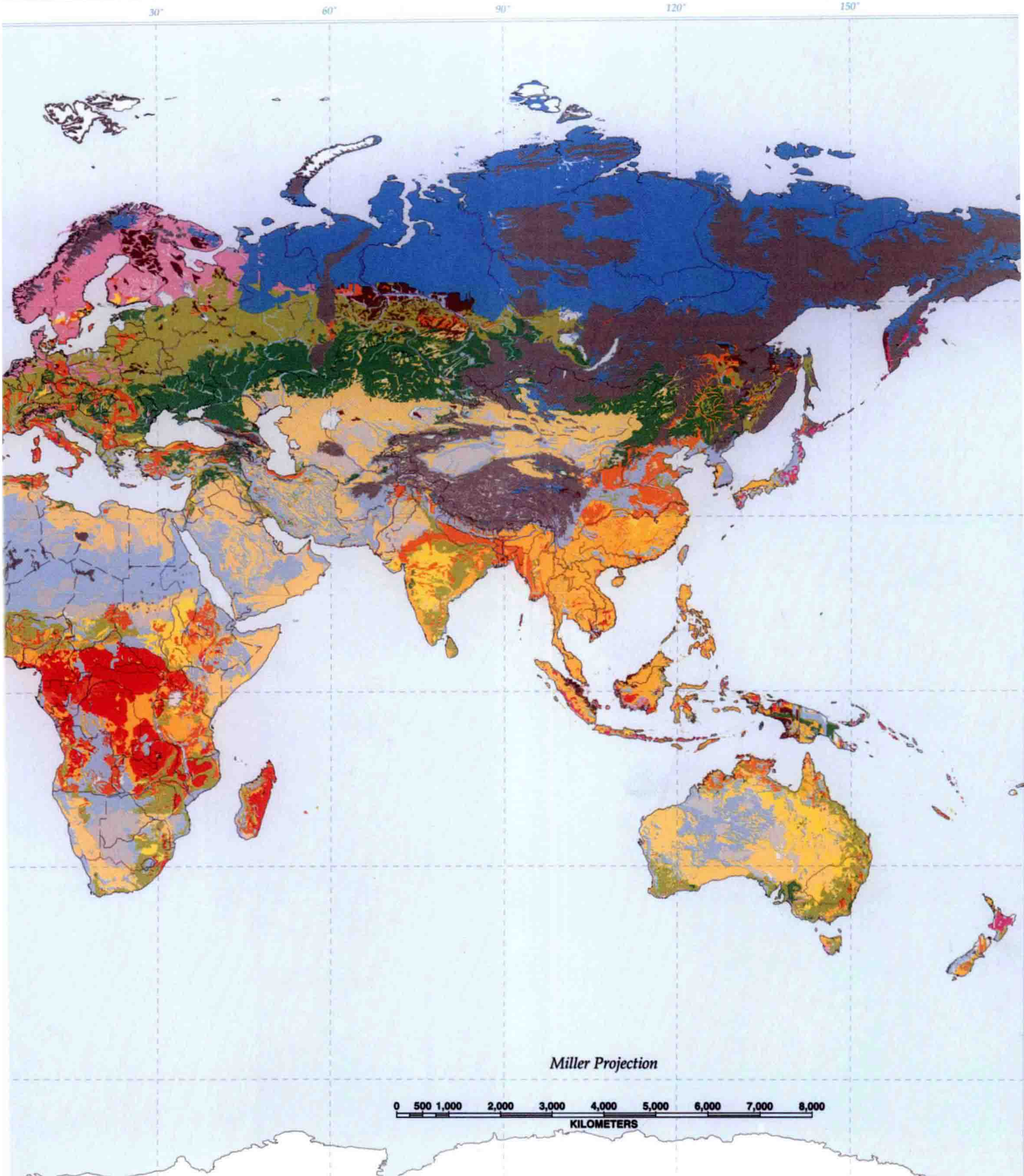

July 1998

Preface

Soils are at the heart of terrestrial ecosystems. An understanding of the soil system is therefore key to the success and environmental harmony of any human endeavor on the land. The importance of soils and the soil system 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.

This book is designed to help make your study of soils both fascinating and intellectually satisfying. 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.

As is the case for its parent book, *The Nature and Properties of Soils*, 14th edition, this newest edition of *Elements 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 the larger forest, range, agricultural, wetland, and constructed ecosystems. This book is designed to 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 is meant to provide both an exciting, accessible introduction to the world of soils and a reliable, comprehensive reference that you will want to keep for your professional bookshelf.

Every chapter has been thoroughly updated with the latest advances, concepts, and applications. This edition includes new discussions on the pedosphere concept, ethnopedology, geophagy, soils and human health, organic farming, engineering properties of soils, nonsilicate colloids, inner- and outer-sphere complexes, effective CEC, the proton-balance approach to soil acidity, cation saturation, acid sulfate soils, acid precipitation, arid region soils, irrigation techniques, biomolecule binding, soil food-web ecology, disease suppressive soils, soil archaea, forest nutrient management, lead contamination, nutrient management, indicators of soil quality, soil ecosystem services, plant production for biofuels, global climate change, and many other topics of current interest in soil science. At the same time, this abridgement of the original book omits or simplifies some of the more technical details, presents fewer chemical equations and calculations, and focuses the text more clearly on the basics of soil science such that a survey of the field is be accomplished in 15 instead of 20 chapters, comprising about 600 instead of nearly 1000 pages. Among the major changes, all the nutrient cycles are now covered in a single chapter, allowing room for the addition of a new chapter on soil pollution and contamination.

In response to their popularity in recent editions, there are 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 include case studies of how soils influenced the Hurricane Katrina levee failures, amelioration of selenium pollution in wetlands, capillary barriers for nuclear waste, the invasion of North American forests by earthworms, runoff farming in ancient deserts, and the debate over nitrate toxicity.

New boxes have also been added to provide detailed calculations for soil water content, profile water holding capacity, cation exchange capacity, and many other numerical problems.

Two extremely popular features of recent editions have been the high quality figures that help soils come alive, as well as the many World Wide Web universal resource locators (URLs) set in the margins of the relevant sections. These link websites developed by colleagues and organizations around the world and expand and elaborate on certain topics in ways that would not be possible in a printed book. These features are made even more effective and convenient on the new and expanded *Companion Website* (available at http://www.pearsonhighered.com/bradyweil/), where you will find beautiful full-color versions of most of the black-and-white figures printed in the book, as well as clickable links to all the URLs given in each chapter. The website also offers practice quizzes for each chapter that provide interactive feedback. These quizzes will both challenge you and build confidence in your growing understanding of the topics and their interrelationships.

Dr. Nyle Brady, having been in retirement for a number of years, decided to stand aside for the writing of the 14th edition of the full book and the 3rd edition of *Elements*, making these the first editions since 1952 not to see his direct participation. However, he remains as first author in recognition of the fact that his vision, wisdom, and inspiration continue to permeate both books. Although the responsibility for writing this edition was solely mine, I certainly could not have made all the improvements just mentioned without the many valuable suggestions, ideas, and corrections sent in by soil scientists, instructors, and students from around the world. I want to especially thank the professors who reviewed major parts of the book: Steve Thien, Kansas State University; Jan-Marie Traynor, County College of Morris; Iin Handayani, Murray State University; William C. Lindemann, New Mexico State University; and Eric Brevik, Dickinson State University. This new edition, like preceding editions, has greatly benefited from such contributions. The high level of professional devotion and camaraderie shared by so many students, teachers, and practitioners of soil science never ceases to amaze and inspire me.

Last, but not least, I wish to express my deep appreciation to Trish, my wife and spiritual partner, for her understanding, patience, encouragement, and sense of humor (exemplified by her joking reference to this book as *Dirts I Have Known*). Her support throughout the process enabled me to complete this labor of love.

About the Authors

Nyle C. Brady, a native of Manassa, Colorado, graduated from Brigham Young University in 1941 with a Bachelor's degree in Chemistry. In 1947 he received his PhD degree in Soil Science from the University of North Carolina. He served on the Cornell faculty from 1947 to 1973, and in 1952 became co-author of the world's most widely used college textbook on Soil Science. He was Head of the Department of Agronomy from July 1955 to December 1963 and served as the Director of the Cornell University Agricultural Experiment Station from September 1965 to July 1973. He was Associate Dean of the New York State College of Agriculture and Life Sciences from October 1970 to July 1973.

Dr. Brady served as the Director of Science and Education for the U.S. Department of Agriculture in Washington, D.C. from December 1963 to September 1965. From July 1973 to July 1981, he was Director General of the International Rice Research Institute in the Philippines. From 1981 to 1989, he served as Senior Assistant Administrator for Science and Technology of the United States Agency for International Development in Washington, D.C. From 1990 to 1994 he was a full time Senior Consultant for collaborative research and development programs of the World Bank in Washington, D.C. and the United Nations Development Program in New York. He is the recipient of four Honorary Doctoral Degrees from Brigham Young University (1979), Ohio State University (1991), University of the Philippines (1991), and N. C. State University (1992).

Ray R. Weil is Professor of Soil Science. He has earned degrees at Michigan State University, Purdue University, and Virginia Tech. Before coming to Maryland, he served in the Peace Corps in Ethiopia, managed a 500 acre organic farm in North Carolina, and was a Lecturer at the University of Malawi. He has become an international leader in sustainable agricultural systems in both developed and developing countries. Published in over 60 scientific journal articles and 6 books, his research focuses on cover crops and organic matter management for enhanced soil quality and nutrient cycling for water quality and sustainability. His research lab developed analytical methods for soil microbial biomass and active soil C that have been adopted by the USDA/NRCS and are used in ecosystem studies world wide. His contributions to improved cropping systems and soil management have been put into practice on farms large and small.

As a University of Maryland professor, Dr. Weil has taught over 5,000 undergraduate and graduate students, addressed over 3,000 farmers and farm advisors at meetings and field days, and helped train hundreds of researchers and managers in various companies and organizations. He has been the major advisor for 38 MS and PhD students. Weil is a Fellow of both the Soil Science Society of America and the American Society of Agronomy. He has twice been awarded a Fulbright Fellowship to support his work in developing countries. The synergism between Dr. Weil's teaching and research, and his ecological approach to soil science have found expression in various editions of this textbook since 1995.

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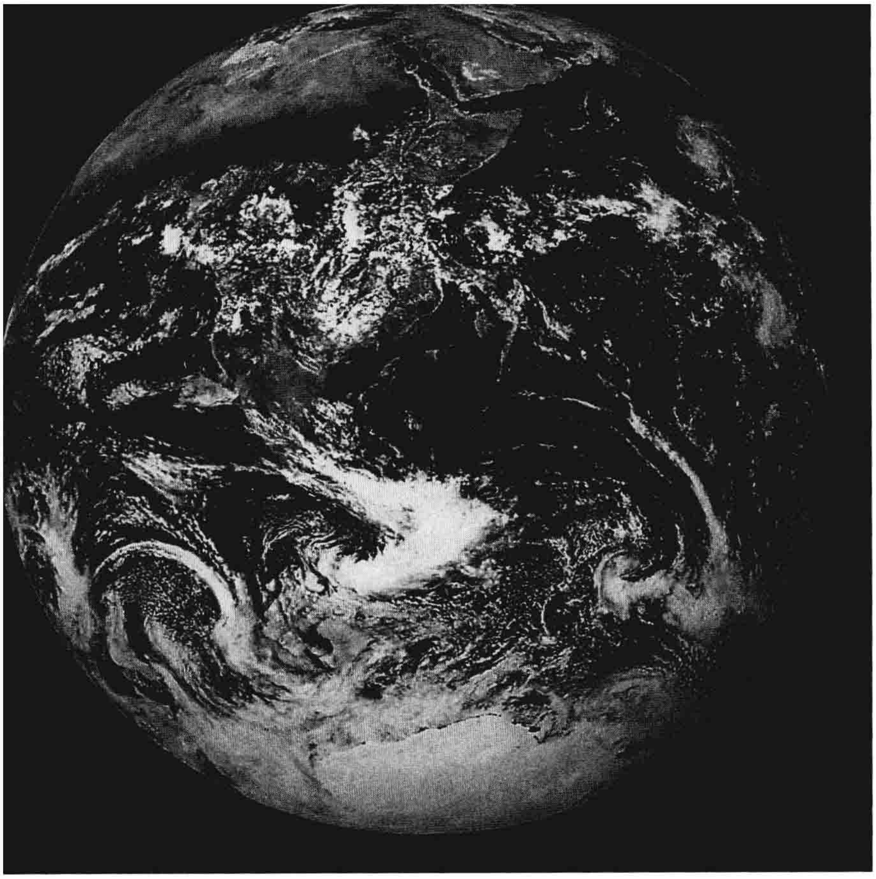


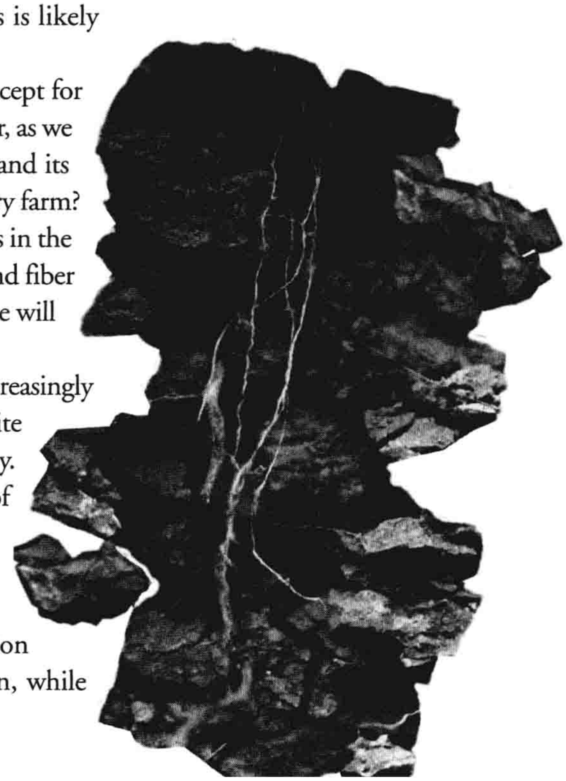
Earth, unique for soil and water. (NASA)

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*

Soils are crucial to life on Earth. From ozone depletion and global warming to rain forest destruction and water pollution, the world's ecosystems are impacted in far-reaching ways by processes carried out in the soil. To a great degree, the quality of the soil determines the nature of plant ecosystems and the capacity of land to support animal life and society. 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 (except for what can be harvested from the oceans). 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 seen in the form of biofuels made from plant products, printers' inks made from soybean oil, and biodegradable plastics synthesized from cornstarch (Figure 1.1).

A stark reality of the 21st century is that the human population that demands all of these products will increase by several billion, while

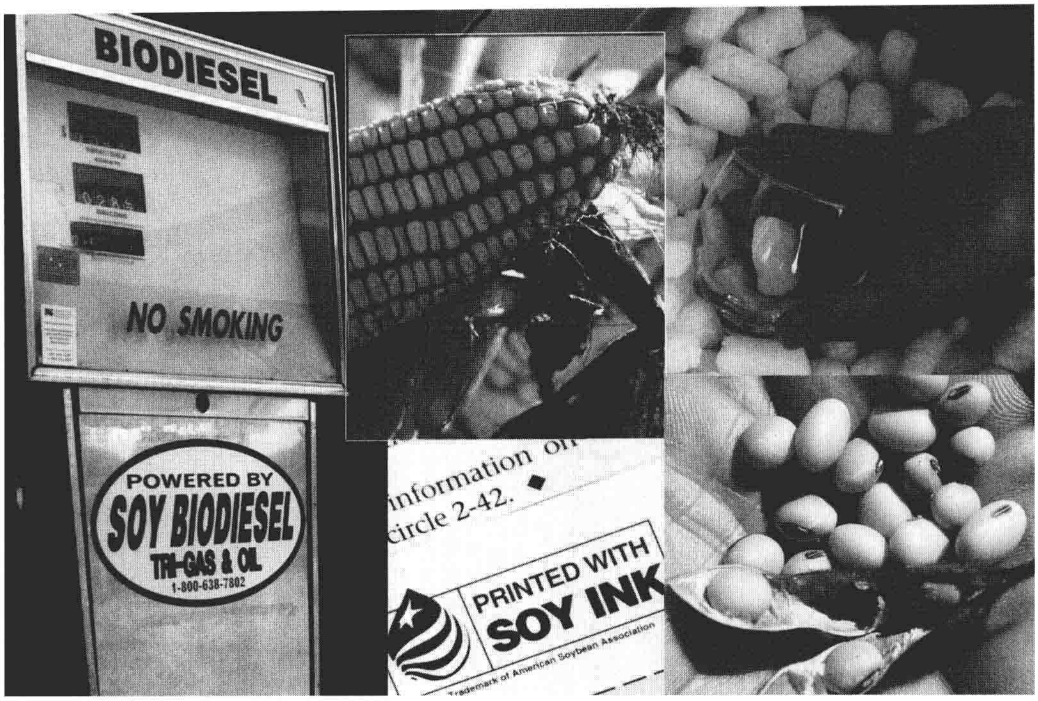


Figure 1.1 *Biofuels (left) produced from crops are far less polluting and have less impact on global warming than petroleum-based fuel. Soybean and other crops can substitute for petroleum to produce nontoxic inks (bottom), plastics, and other products. Cornstarch can be made into biodegradable plastics for such products as plastic bags and foam packing "peanuts" (upper right).* (Photos courtesy of R. Weil)

the resource base available to provide them is actually *shrinking* because of soil degradation and urbanization. It is clear that we must greatly improve our understanding and management of the soil resource if we as a species are to survive and if we are to leave enough habitat for the survival of the other creatures that share this planet with us.

The Earth, our unique home in the vastness of the universe, is covered with life-sustaining air, water, and soil. However, we live in an age when human activities are changing the very nature of all three. Depletion of the ozone layer in the stratosphere is threatening to overload us with ultraviolet radiation. Increasing concentrations of carbon dioxide and methane gases are warming the planet and destabilizing the global climate. Tropical rain forests, and the incredible array of plant and animal species they contain, are disappearing at an unprecedented rate. Groundwater supplies are being contaminated in many areas and depleted in others. 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 is a defining challenge of our times.

New understandings and new technologies will be needed to protect the environment and, at the same time, produce food and biomass to support society. The study of soil science has never been more important for foresters, farmers, engineers, natural resource managers, and ecologists alike.

1.1 SOILS AS MEDIA FOR PLANT GROWTH

Plant germination video: http://plantsinmotion.bio.indiana.edu/plantmotion/earlygrowth/germination/germ.html

In any ecosystem, whether your backyard, a farm, a forest, or a regional watershed, soils play six key roles (Figure 1.2). First among these is the support of plant growth. Soils provide a medium for plant roots and supply nutrient elements that are essential to the entire plant. Properties of the soil often determine the nature of the vegetation present and, indirectly, the number and types of animals (including people) that the vegetation can support.

When we think of the forests, prairies, lawns, and crop 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

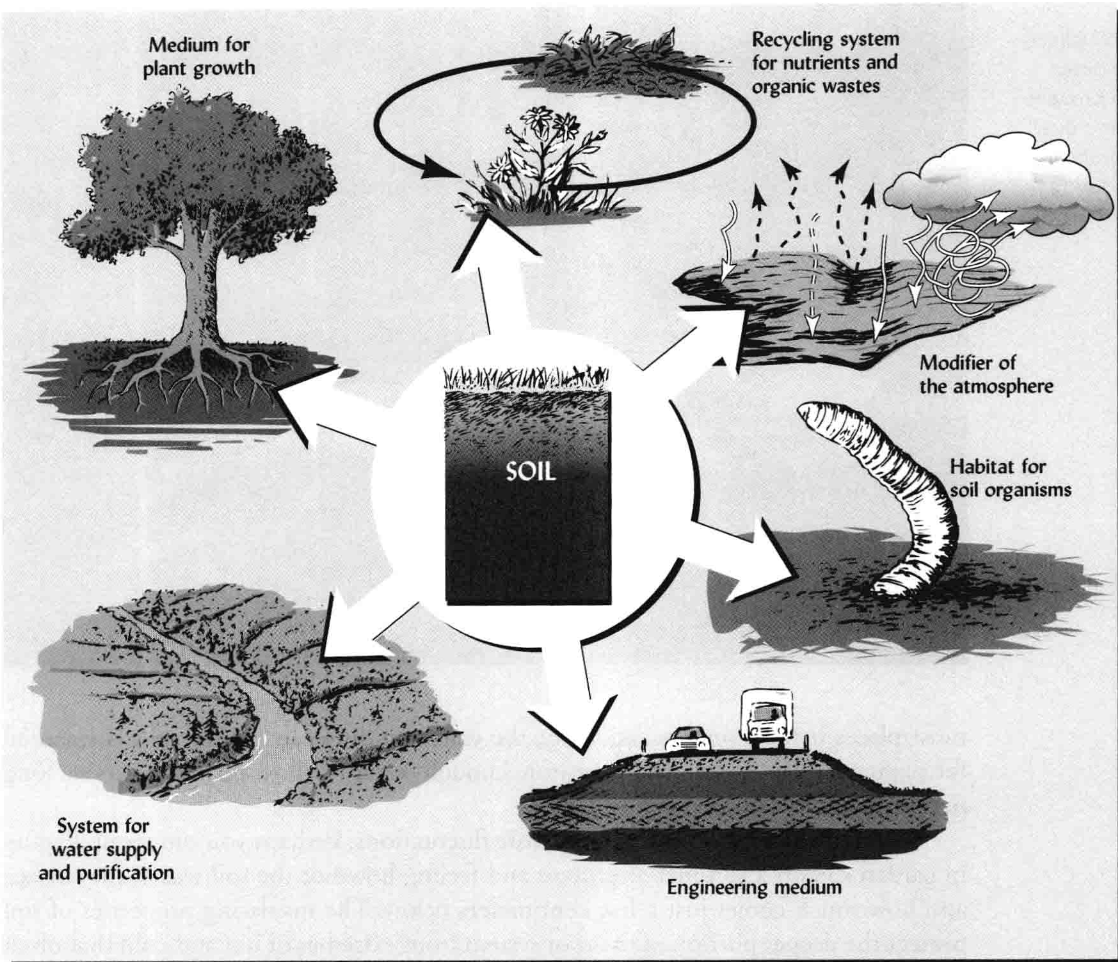


Figure 1.2
The many functions of soil can be grouped into six crucial ecological roles.

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

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).

Plant roots depend on the process of respiration to obtain energy. 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*—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 rainwater 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. Because plants use water continuously, but in

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 R. Weil)

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 (see Figure 1.4).

The soil also moderates temperature fluctuations. Perhaps you can recall digging in garden soil 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 the soil surface.

Phytotoxic substances in soils may result from human activity, or they may be produced by plant roots, by microorganisms, or by natural chemical reactions. A good

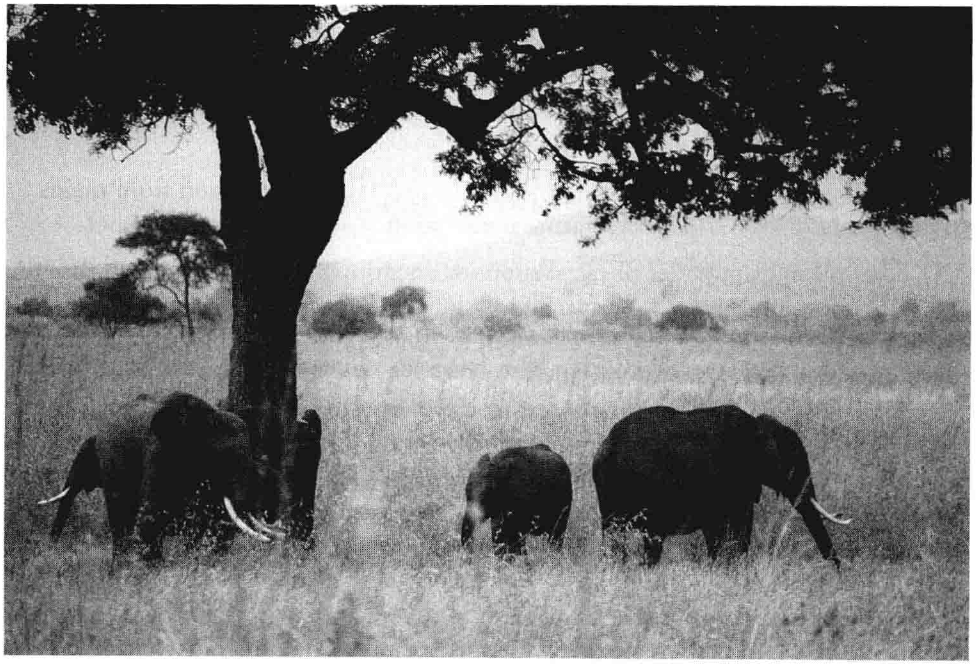


Figure 1.4
A family of African elephants finds welcome shade under the leafy canopy of a huge acacia tree in this East African savanna. The photo was taken in the middle of a long dry season; no rain had fallen for almost five months. The tree roots are still using water from the previous rainy season 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 R. Weil)

soil will protect plants from toxic concentrations of such substances by ventilating gases, by decomposing or adsorbing organic toxins, or by suppressing toxin-producing organisms. On the other hand, some microorganisms in soil produce growth-stimulating compounds that may improve plant vigor.

Soils supply plants with **mineral nutrients**. A fertile soil will provide a continuing supply of dissolved mineral nutrients in amounts and relative proportions appropriate for optimal plant growth. The nutrients include such metallic elements as potassium, calcium, iron, and copper, as well as such nonmetallic elements as nitrogen, sulfur, phosphorus, and boron. The plant takes these elements out of the soil solution and incorporates most of them into the thousands of different organic compounds that constitute plant tissue. Animals usually obtain their mineral nutrients indirectly from the soil by eating plants. Under some circumstances, animals (including humans) satisfy their craving for minerals by ingesting soil directly (Box 1.1).

Interactive periodic table—look up the essential elements: www.webelements.com

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). Essential elements used by plants in relatively large

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 15), but most sophisticated residents of industrial countries, anthropologists and nutritionists included, find it hard to believe that anyone would *purposefully* ingest soil. Yet a long history of documented 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 Uganda (Figure 1.5). Immigrants from south Asia in the United Kingdom have brought the practice of soil eating to such cities as London and Birmingham. 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.

Figure 1.5
Bars of clay soil sold for human consumption in a shop in Kampala, Uganda. (Photo courtesy of Peter W. Abrahams, University of Wales)

People usually do not eat just any soil but seek out a particular soil, be it the hardened clay of a termite nest, the soft, white soil in a particular riverbank, or the dark clay from a certain deep soil layer. People in different places and circumstances seek to consume different types of soils—some seek calcium-rich soils, others soil with high amounts of certain clays; still others seek red soils rich in iron. Interestingly, unlike many other animals, humans rarely appear to eat soil to obtain salt. Possible benefits from eating soil also vary and may include mineral nutrient supplementation (especially iron), detoxification of ingested poisons (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!

[a]This box is largely based on a fascinating book chapter by Abrahams (2005) and a review article by Stokes (2006).

Table 1.1
ELEMENTS ESSENTIAL 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 ($\mathbf{Mg}^{2+}$)	Iron ($\mathbf{Fe}^{2+}$)
	Nitrogen ($\mathbf{N}H_4^+$)	Manganese ($\mathbf{Mn}^{2+}$)
	Potassium ($\mathbf{K}^+$)	Nickel ($\mathbf{Ni}^{2+}$)
		Zinc ($\mathbf{Zn}^{2+}$)
	Anions:	*Anions:*
	Nitrogen ($\mathbf{N}O_3^-$)	Boron ($H_3\mathbf{B}O_3$, $H_4\mathbf{B}O_4^-$)
	Phosphorus ($H_2\mathbf{P}O_4^-$, $H\mathbf{P}O_4^{2-}$)	Chlorine ($\mathbf{Cl}^-$)
	Sulfur ($\mathbf{S}O_4^{2-}$)	Molybdenum ($\mathbf{Mo}O_4^{2-}$)

[a] Many other elements are taken up from soils by plants but are not *essential* for plant growth (see Epstein and Bloom, 2005).

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
***C**losed **M**o**n**day **Mo**rning and **Ni**ght*
S**ee You **Z**oo**n**, the **Mg

The bold letters indicate the chemical elements in this phrase; finding copper (Cu) and zinc (Zn) may require some 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. Although hydroponic production on a small scale for a few high-value plants is feasible, production of the world's food and fiber and maintenance of natural ecosystems will always depend on millions of square kilometers of productive soils.

1.2 SOIL AS REGULATOR OF WATER SUPPLIES

For progress to be made in improving water quality, we must recognize that most of the water in our rivers, lakes, estuaries, and aquifers has either traveled through the soil or flowed over its surface. Imagine, for example, a heavy rain falling on the hills surrounding a river. If the soil allows the rain to soak in, some of the water may be stored in the soil and used by the trees and other plants, while some may seep slowly down through the soil layers to the groundwater, eventually entering the river over a period of months or years as base flow. If the water is contaminated, as it soaks