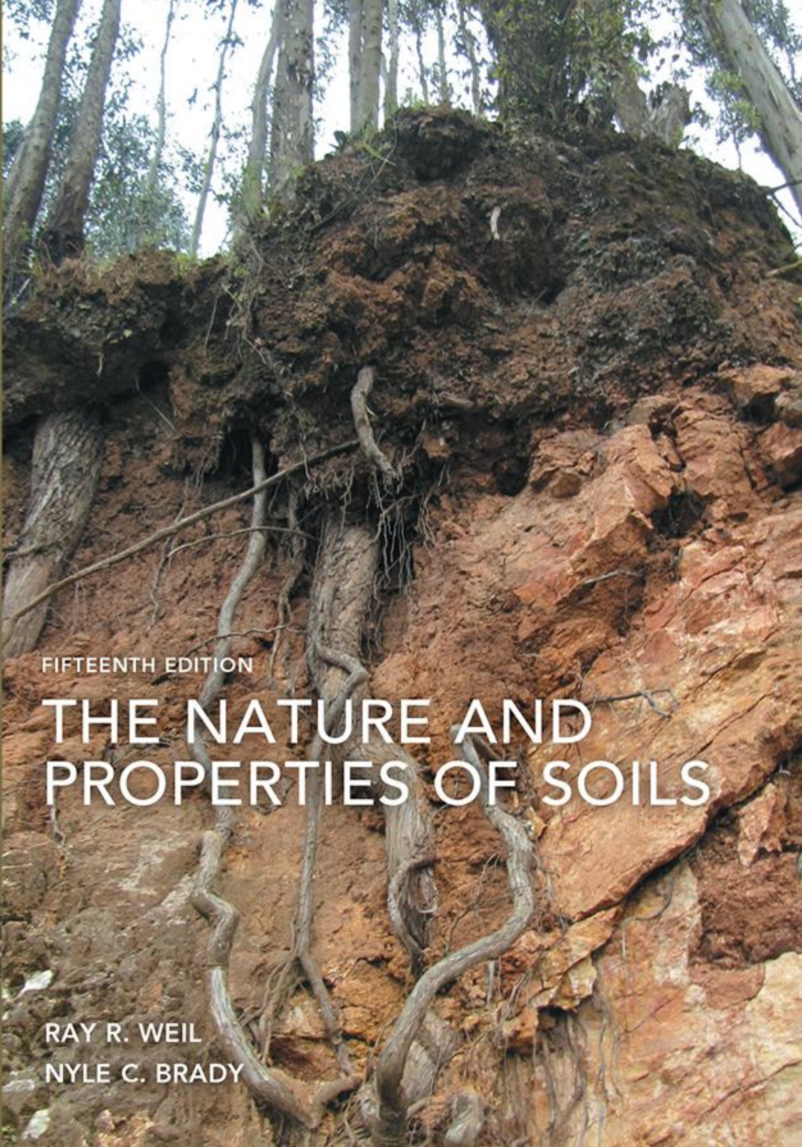


FIFTEENTH EDITION

THE NATURE AND PROPERTIES OF SOILS

RAY R. WEIL
NYLE C. BRADY

THE NATURE AND PROPERTIES OF SOILS

This page intentionally left blank

THE NATURE AND PROPERTIES OF SOILS

FIFTEENTH EDITION

Ray R. Weil
Professor of Soil Science
University of Maryland

Nyle C. Brady (late)
Professor of Soil Science, Emeritus
Cornell University

PEARSON

Boston Columbus Indianapolis New York San Francisco Hoboken
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Executive Editor: Daryl Fox
Editorial Director: Andrew Gilfillan
Program Manager: Susan Watkins
Project Manager: Rex Davidson
Editorial Assistant: Lara Dimmick
Vendor Project Manager: Lumina Datamatics
SVP Field Marketing, NA: David Gesell
Senior Marketing Manager, Careers and Associations: Darcy Betts
Field Marketing Manager, Careers and Associations: Thomas Hayward
Senior Marketing Coordinator: Les Roberts
Senior Art Director: Diane Y. Ernsberger
Procurement Specialist: Deidra Skahill
Cover Designer: Carie Keller, Cenveo, Inc.
Cover Photo: Ray Weil

This book was set in Stone Serif by Lumina Datamatics. It was printed and bound by RR Donnelley, Willard. The cover was printed by Phoenix Color Corp.

Library of Congress Cataloging-in-Publication Data

Names: Weil, Ray R., author. | Brady, Nyle C., author.
Title: The nature and properties of soils / Ray R. Weil, Nyle C. Brady
Description: Fifteenth edition. | Columbus : Pearson, 2016.
Identifiers: LCCN 2016008568 | ISBN 9780133254488
Subjects: LCSH: Soil science. | Soils.
Classification: LCC S591 .B79 2016 | DDC 631.4--dc23
LC record available at http://lccn.loc.gov/2016008568

PEARSON

ISBN-13: 978-0-13-325448-8
ISBN-10: 0-13-325448-8

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

This page intentionally left blank

Contents

NOTE: Every effort has been made to provide accurate and current Internet information in this book. However, the Internet and information posted on it are constantly changing, and it is inevitable that some of the Internet addresses listed in this textbook will change.

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

This page intentionally left blank

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

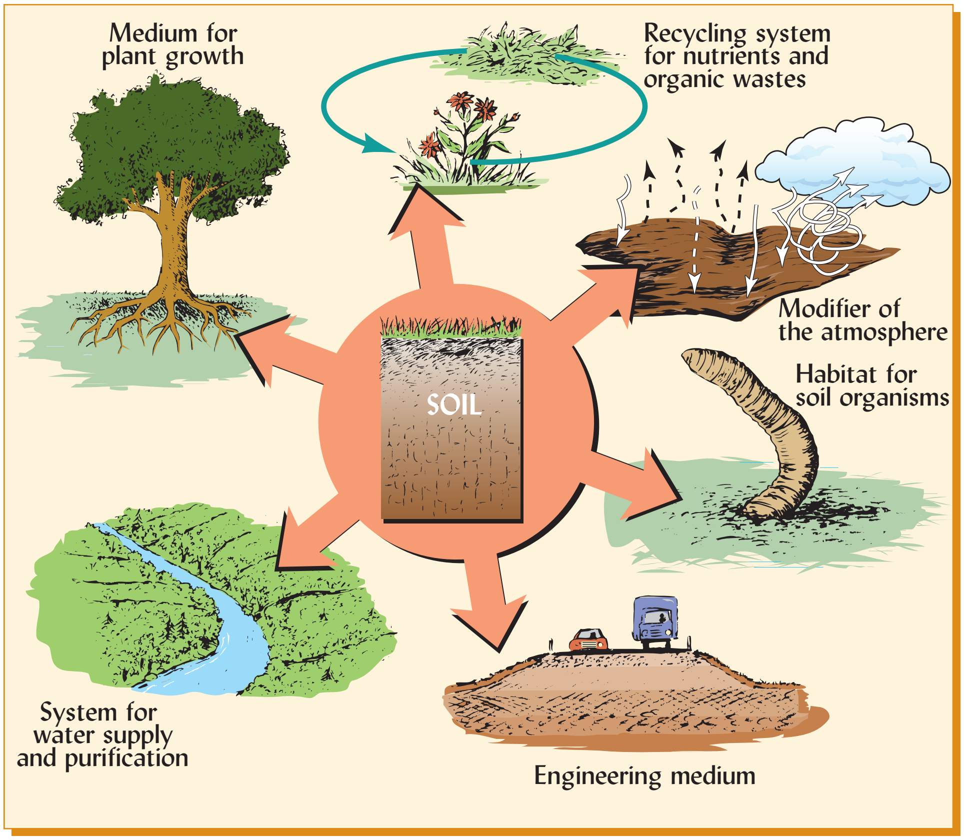


Figure 1.2 *The many functions and ecosystem services performed by soil can be grouped into six crucial ecological roles.* (Diagram courtesy of Ray R. Weil)

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 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. *Fifth*, soils are alive and are home to creatures from small mammals and reptiles to tiny insects to microorganisms of unimaginable numbers and diversity. *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 **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 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.

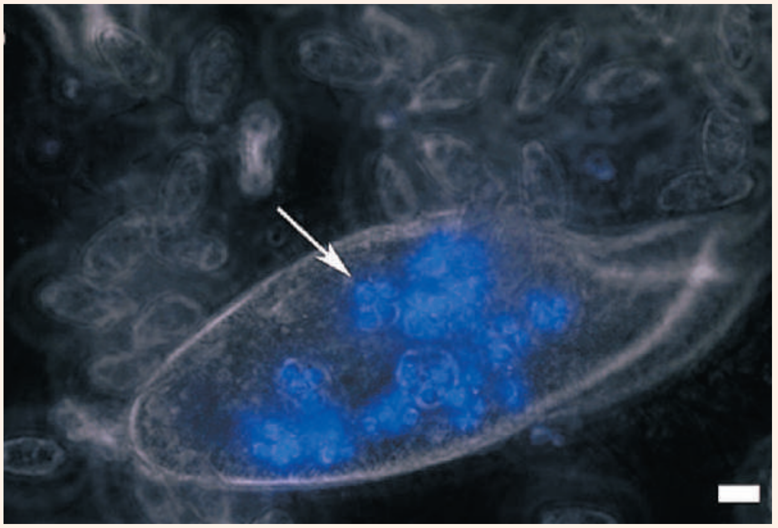


Figure 1.9 *Balance of nature in the soil ecosystem. This Paramecium, a single celled soil animal (protista) ingests and kills spores of the human pathogenic fungus Cryptococcus. Arrow shows spores inside the paramecium; white scale bar = 1μm. Microscopic image from Frager et al. (2010).*

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).

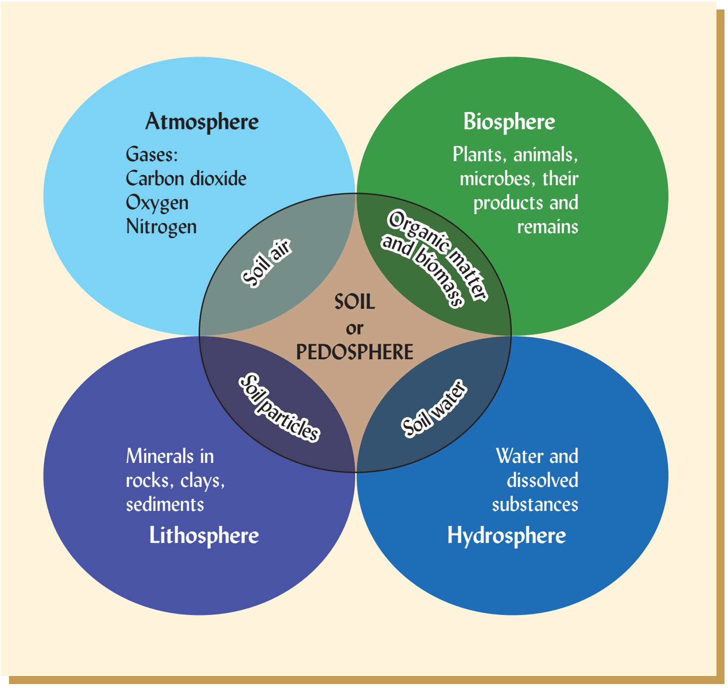
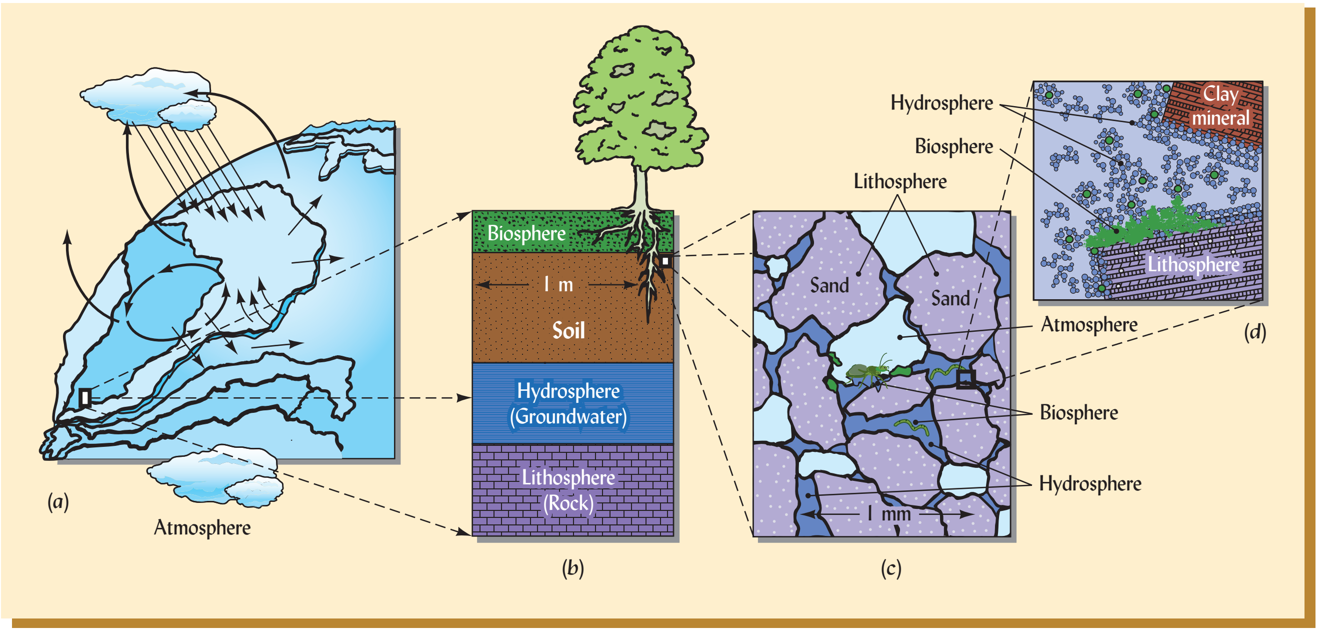


Figure 1.12 *The pedosphere, where the worlds of rock (the lithosphere), air (the atmosphere), water (the hydrosphere), and life (the biosphere) all meet. The soil as interface can be understood at many different scales. At the kilometer scale* (a)*, soil participates in global cycles of rock weathering, atmospheric gas changes, water storage and partitioning, and the life of terrestrial ecosystems. At the meter scale* (b)*, soil forms a transition zone between the hard rock below and the atmosphere above—a zone through which surface water and groundwater flow and in which plants and other living organisms thrive. A thousand times smaller, at the millimeter scale* (c)*, mineral particles form the skeleton of the soil that defines pore spaces, some filled with air and some with water, in which tiny creatures lead their lives. Finally, at the micrometer and nanometer scales* (d)*, soil minerals (lithosphere) provide charges, reactive surfaces that adsorb water and cations dissolved in water (hydrosphere), gases (atmosphere), and bacteria and organic matter (biosphere).*
(Diagram courtesy of Ray R .Weil)



also refer to this material as *dirt*, especially when it is found where it is not welcome (e.g., in your clothes or under your fingernails).

A soil is a three-dimensional natural body in the same sense that a mountain, lake, or valley is. *The soil* is a collection of individually different soil bodies, often said to cover the land as the peel covers an orange. However, while the peel is relatively uniform around the orange, the soil is highly variable from place to place on Earth. One of the individual bodies, *a soil*, is to *the soil* as an individual tree is to the Earth's vegetation. Just as one may find sugar maples, oaks, hemlocks, and many other species of trees in a particular forest, so, too, might one find Los Osos loams, Altamont clays, San Benito clay loams, Diablo silty clays, and other kinds of soils in a particular landscape.

Soils are natural bodies composed of soil (the material just described) *plus* roots, animals, rocks, artifacts, and so forth. By dipping a bucket into a lake you may sample some of its water. In the same way, by making a hole in a soil, you may retrieve some soil. Thus, you can take a sample of soil or water into a laboratory and analyze its contents, but you must go out into the field to study a soil or a lake.

In most places, the rock exposed at the Earth's surface has crumbled and decayed to produce a layer of unconsolidated debris overlying the hard, unweathered rock. This unconsolidated layer is called the ***regolith*** (Figure 1.13) and varies in thickness from virtually nonexistent in some places (i.e., exposed bare rock) to tens of meters in other places. Where the underlying rock has weathered in place to the degree that it is loose enough to be dug with a spade, the term **saprolite** is used. In other cases, regolith materials have been transported many kilometers from the site of its initial formation and then deposited over the bedrock which it now covers. Thus, regolith material may or may not be related to the rock now found below it.

Through their biochemical and physical effects, living organisms such as bacteria, fungi, and plant roots have altered the upper part—and, in many cases, the entire depth—of the regolith. Here, at the interface between the worlds of rock, air, water, and living things, soil is born. The transformation of inorganic rock and debris into a living soil is one of nature's most fascinating displays. Although generally hidden from everyday view, the soil and regolith can often be seen in road cuts and other excavations.

A soil is the product of both destructive and creative (synthetic) processes. Weathering of rock and microbial decay of organic residues are examples of destructive processes, whereas the formation of new minerals and new stable organic-mineral complexes are examples of synthesis. Perhaps the most striking result of synthetic processes is the formation of contrasting layers called **soil horizons**. The development of these horizons in the upper regolith is a unique characteristic of soil that sets it apart from the deeper regolith materials (Figure 1.13).

Soil scientists specializing in **pedology** (*pedologists*) study soils as natural bodies, the properties of soil horizons, and the relationships among soils within a landscape. Other soil scientists, called **edaphologists**, focus on the soil as habitat for living things, especially for

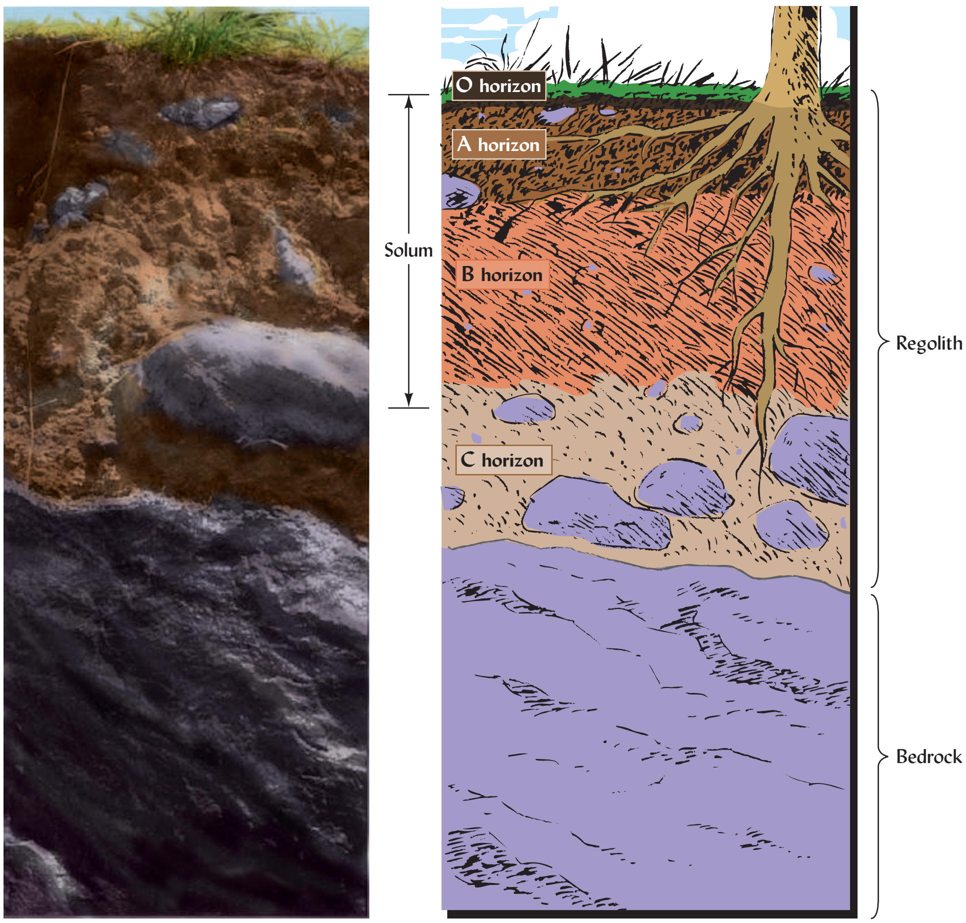


Figure 1.13 *Relative positions of the regolith, its soil, and the underlying bedrock. Note that the soil is a part of the regolith and that the A and B horizons are part of the* **solum** *(from the Latin word* solum, *which means soil or land). The C horizon is the part of the regolith that underlies the solum but may be slowly changing into soil in its upper parts. Sometimes the regolith is so thin that it has been changed entirely to soil; in such a case, soil rests directly on the bedrock.* (Photo courtesy of Ray R. Weil)

plants. For both types of study it is essential to examine soils at all scales and in all three dimensions (especially the vertical dimension).

1.10 THE SOIL PROFILE AND ITS LAYERS (HORIZONS)

Soil scientists often dig a large hole, called a *soil pit* (e.g. Figure 19.6), usually several meters deep and about a meter wide, to expose soil horizons for study. The vertical section exposing a set of horizons in the wall of such a pit is termed a ***soil profile***. Road cuts and other ready-made excavations can expose soil profiles and serve as windows to the soil. In an excavation open for some time, horizons may be more clearly seen if a fresh face is exposed by scraping off a layer of material several centimeters thick from the pit wall. Observing how soils exposed in road cuts vary from place to place can add a fascinating new dimension to travel. Once you have learned to interpret the different horizons (see Chapter 2), soil profiles tell you much about the environment and history of a region as well as warn you about potential problems in using the land.

Horizons within a soil may vary in thickness and have somewhat irregular boundaries, but generally they parallel the land surface (Figure 1.14). This alignment is expected since the differentiation of the regolith into distinct horizons is largely the result of influences such as air, water, solar radiation, and plant material, originating at the soil–atmosphere interface. Because the weathering of the regolith occurs first at the surface and works its way down, the uppermost layers have been changed the most, while the deepest layers are most similar to the original regolith, which is referred to as the soil's ***parent material***. In places where the regolith was originally rather uniform in composition, the material below the soil may have a similar composition to the parent material from which the soil formed. In other cases, the regolith

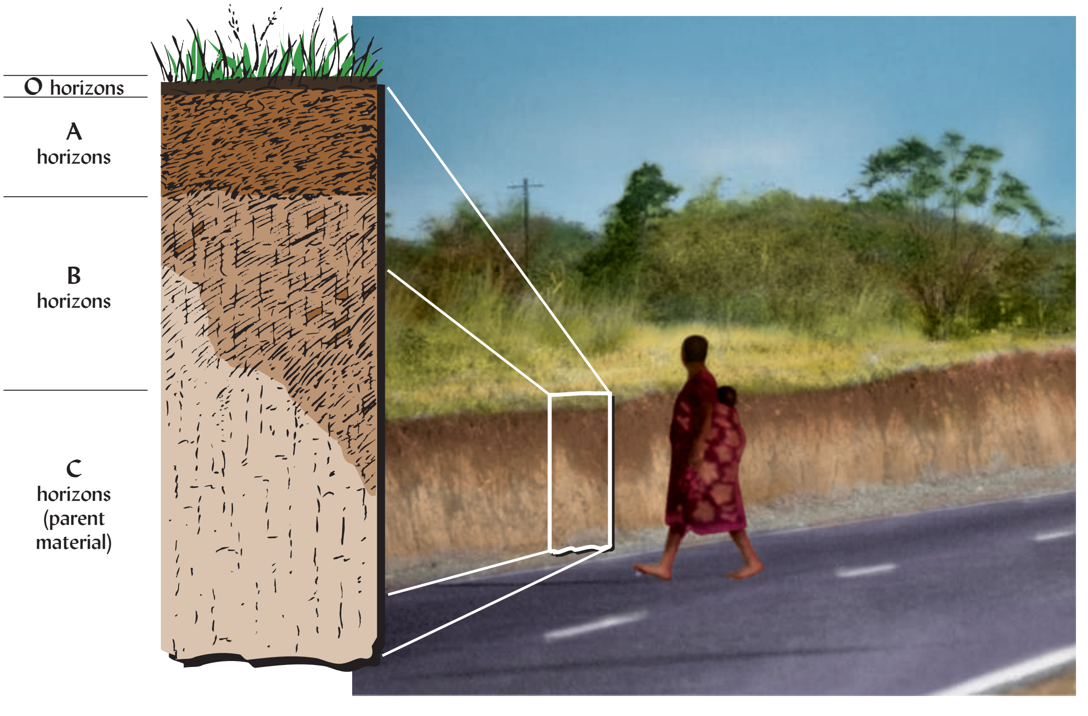


Figure 1.14 *This road cut in central Africa reveals soil layers or horizons that parallel the land surface. Taken together, these horizons comprise the profile of this soil, as shown in the enlarged diagram. The surface litter or O horizon may be very thin or nonexistent under this type of vegetation. The upper horizons are designated* A horizons. *They are usually higher in organic matter and darker in color than the lower horizons. Some constituents, such as iron oxides and clays, have been moved downward from the A horizons by percolating rainwater. The lower horizon, called a* B horizon, *is sometimes a zone in which clays and iron oxides have accumulated, and in which distinctive structure has formed. The presence and characteristics of the horizons in this profile distinguish this soil from the thousands of other soils in the world.* (Photo courtesy of Ray R. Weil)

material has been transported by wind, water, or glaciers and deposited on top of dissimilar material. In such a case, the regolith material found below a soil may be quite different from the upper layer of regolith in which the soil is formed.

In undisturbed ecosystems, especially forests, organic remains of fallen leaves and other plant and animal materials tend to accumulate on the surface. There they undergo varying degrees of physical and biochemical breakdown and transformation so that layers of older, partially decomposed materials may underlie the freshly added debris. Together, these organic layers at the soil surface are designated the ***O horizons*** (Figure 1.15).

Soil animals and percolating water move some of these organic materials downward to intermingle with the mineral grains of the regolith. These join the decomposing remains of plant roots to form organic materials that darken the upper mineral layers. Also, because weathering tends to be most intense nearest the soil surface, in many soils the upper layers lose

Figure 1.15 *A piece of the O horizon from a deciduous forest floor in Vermont, USA.* (Photo courtesy of Ray R. Weil)

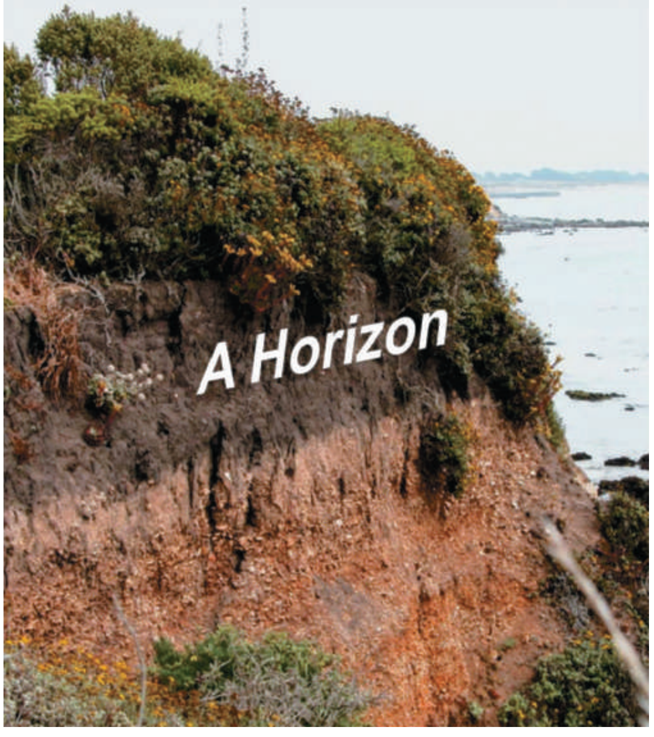


Figure 1.16 *Decaying plant materials have darkened a thick A horizon that caps this soils along the central California coast.* (Photo courtesy of Ray R. Weil)

some of their clay or other weathering products by leaching to the horizons below. ***A horizons*** are the layers nearest the surface that are dominated by mineral particles but have been darkened by the accumulation of organic matter (Figure 1.16).

In some soils, intensely weathered and leached horizons that have not accumulated organic matter occur in the upper part of the profile, usually just below the A horizons. These horizons are designated ***E horizons*** (Figures 1.17 and 1.18).

The layers underlying the A and O horizons contain comparatively less organic matter than the horizons nearer the surface. Varying amounts of silicate clays, iron and aluminum oxides, gypsum, or calcium carbonate may accumulate in the underlying horizons. The accumulated materials may have been washed down from the horizons above, or they may have been formed in place through the weathering process. These underlying layers are referred to as ***B horizons*** (Figure 1.18).

Plant roots and microorganisms often extend below the B horizon, especially in humid regions, causing chemical changes in the soil water, some biochemical weathering of the regolith, and the formation of ***C horizons***. The C horizons are the least weathered part of the soil profile.

In some soil profiles, the component horizons are very distinct in color, with sharp boundaries that can be seen easily by even novice observers. In other soils, the color changes between horizons may be very gradual, and the boundaries more difficult to locate. However, color is only one of many properties by which one horizon may be distinguished from the horizon above or below it (see Figure 1.18). The study of soils in the field is often quite a sensual activity that requires all the senses to delineate the horizons present. In addition to seeing the

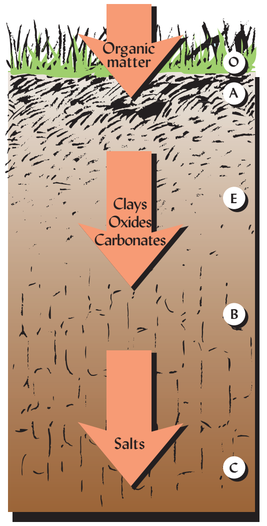


Figure 1.17 *Horizons begin to differentiate as materials are added to the upper part of the profile and other materials are translocated to deeper zones. Under certain conditions, usually associated with forest vegetation and high rainfall, a leached E horizon forms between organic matter-rich A and the B horizons. If sufficient rainfall occurs, soluble salts will be carried below the soil profile, perhaps all the way to the groundwater. Many soils (e.g., the soil in Figure 1.14) lack one or more of the five horizons shown here.* (Diagram courtesy of Ray R. Weil)

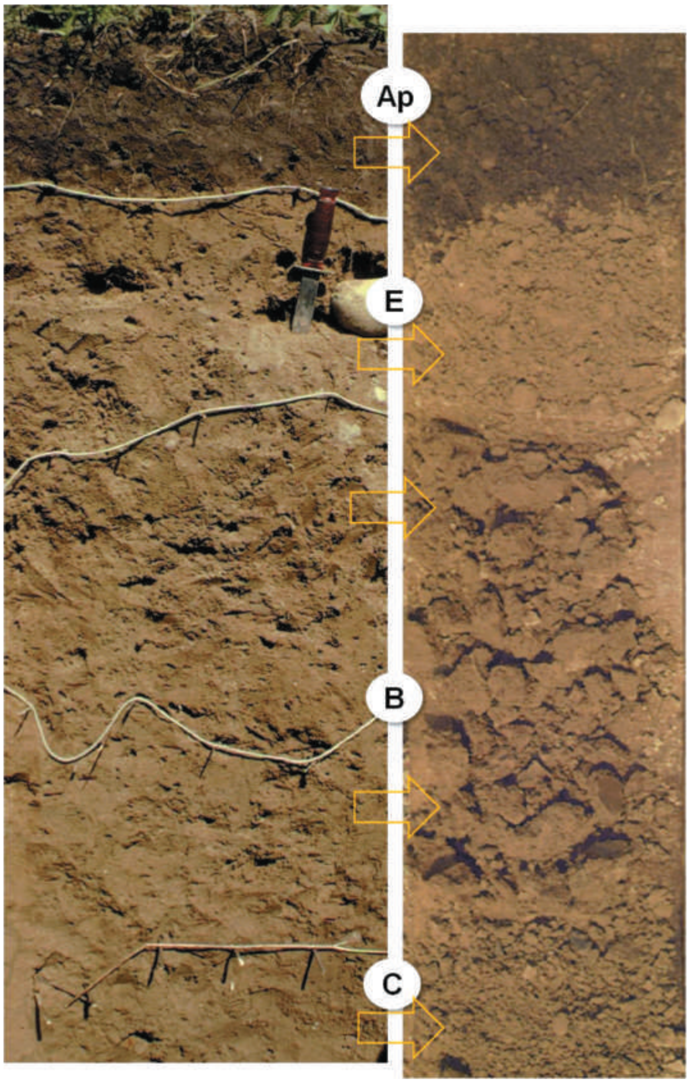


Figure 1.18 (Left) *This soil profile was exposed by digging a pit about 2 meters deep in a well-developed soil (a Hapludalf) in southern Michigan. The top horizon can be easily distinguished because it has a darker color than those below it. However, some of the horizons in this profile are difficult to discern on the basis of color differences, especially in a photo. The white string was attached to the profile to clearly demarcate some of the horizon boundaries. Then a trowel full of soil material was removed from each horizon and placed on a board, at right. It is clear from the way the soil either crumbled or held together that soil material from horizons with very similar colors may have very different physical properties.* (Photos courtesy of Ray R. Weil)

colors in a profile, a soil scientist may feel, smell, and listen[3] to the soil, as well as conduct chemical tests, in order to distinguish the horizons present.

1.11 TOPSOIL AND SUBSOIL

The organically enriched A horizon at the soil surface is sometimes referred to as ***topsoil***. Plowing and cultivating a soil homogenizes and modifies the upper 10 to 25 cm of the profile to form a plow layer. The plow layer may remain long after cultivation has ceased. For example, in a New England forest that has regrown on abandoned farmland, you may still see the smooth boundary between the century-old plowed layer and the lighter-colored, undisturbed soil below.

In cultivated soils, the majority of plant roots can be found in the topsoil as that is the zone in which the cultivator can most readily enhance the supply of nutrients, air, and water by mixing in organic and inorganic amendments, loosening the structure, and applying irrigation. Sometimes the plow layer is removed from a soil and sold as topsoil for use at another site. This use of topsoil is especially common to provide a rooting medium suitable for lawns and shrubs around newly constructed buildings, where the original topsoil was removed or buried and the underlying soil layers were exposed during grading operations (Figure 1.19).

The soil layers that underlie the topsoil are referred to as ***subsoil***. Although usually hidden from view, the subsoil horizons can greatly influence most land uses. Much of the water needed by plants is stored in the subsoil. Many subsoils also supply important quantities of certain plant nutrients. The properties of the topsoil are commonly far more conducive to plant growth than those of the subsoil. In cultivated soils, therefore, productivity is often

Figure 1.19 *The large gray-brown mound of material in the foreground at this construction site consists of topsoil (A horizon material) carefully separated from the lower horizons and pushed aside during initial grading operations. Behind it is a similar sized pile of reddish-brown soil from the lower (subsoil) horizons. The stockpiles were then seeded with grasses to protect from erosion. The subsoil material will be used during construction to fill in low spots and build foundations and roadbeds. After construction activities are complete, the stockpiled topsoil (front pile) will be used in landscaping the grounds around the new buildings.* (Photo courtesy of Ray R. Weil)

[3]For example, the grinding sound emitted by wet soil rubbed between one's fingers indicates a sandy nature.

correlated with the thickness of the topsoil layer. Subsoil layers that are too dense, acidic, or wet can impede root growth. It may be extremely difficult and expensive to physically or chemically modify the subsoil.

Many of the chemical, biological, and physical processes that occur in the upper soil layers also take place to some degree in the C horizons, which may extend deep into the underlying saprolite or other regolith material. Traditionally, the lower boundary of the soil has been considered to occur at the greatest rooting depth of the natural vegetation, but soil scientists are increasingly studying layers below this in order to understand ecological processes of the critical zone such as groundwater pollution, parent material weathering, and biogeochemical cycles (Box 1.3).

BOX 1.3

USING INFORMATION FROM THE ENTIRE SOIL PROFILE

Soils are three-dimensional bodies that carry out important ecosystem processes at all depths in their profiles. Depending on the particular application, the relevant information may come from soil layers as shallow as the upper 1 or 2 cm or as deep as the lowest layers of saprolite (Figure 1.20).

For example, the upper few centimeters of soil often hold the keys to plant growth and biological diversity, as well as to certain hydrologic processes. Here, at the interface between the soil and the atmosphere, living things are most numerous and diverse. Forest trees largely depend for nutrient uptake on a dense mat of fine roots growing in this zone. The physical condition of this thin surface layer may also determine whether rain will soak in or run downhill on the land surface. Certain pollutants, such as lead, are also concentrated in this zone. For many types of soil investigations it will be necessary to sample the upper few centimeters separately so that important conditions are not overlooked.

On the other hand, it is equally important not to confine one's attention to the easily accessible "topsoil," for many soil properties are to be discovered only in the deeper layers. Plant-growth problems are often related to inhospitable conditions in the B or C horizons that restrict the penetration of roots. Similarly, the great volume of these deeper layers may control the amount of plant-available water held by a soil. For the purposes of recognizing or mapping different types of soils, the properties of the B horizons are often paramount. Not only is this the zone of major accumulations of minerals and clays, but the layers nearer the soil surface may be too quickly altered by management and soil erosion to be considered a reliable basis for soil classification.

In deeply weathered regoliths, the lower C horizons and saprolite play important roles. These layers, generally at depths below 1 or 2 meters and often as deep as 5 to 10 meters, greatly affect the suitability of soils for most urban uses that involve construction or excavation. The proper functioning of on-site sewage disposal systems and the stability of building foundations are often determined by regolith properties at these depths. Likewise, processes that control the movement of pollutants to groundwater or the weathering of geologic materials may occur at depths of many meters. These deep layers also have major ecological influences because, although the intensity of biological activity and plant rooting may be quite low, the total impact can be great as a result of the enormous volume of soil that may be involved. This is especially true of forest systems in warm climates.

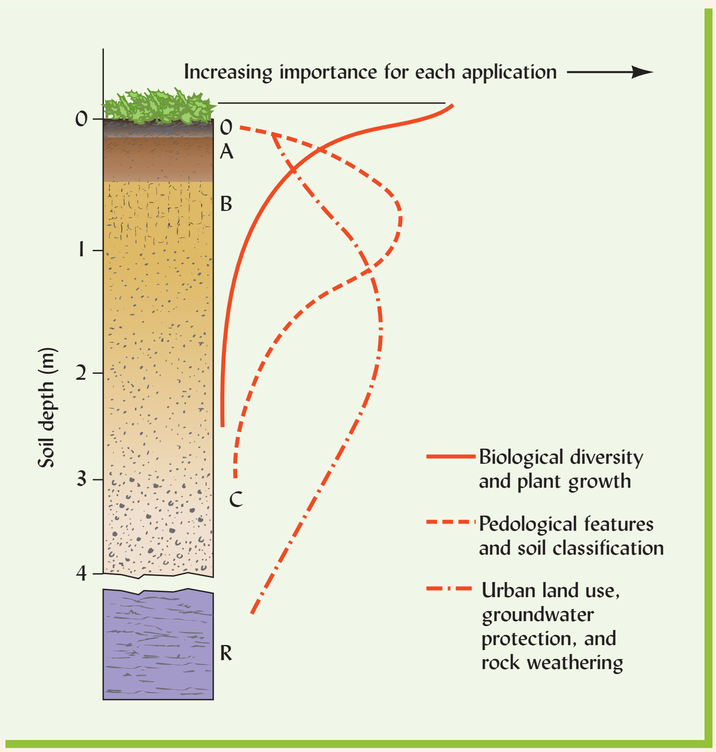


Figure 1.20 *Information important to different soil functions and applications is most likely to be obtained by studying different layers of the soil profile.* (Diagram courtesy of Ray R. Weil)

1.12 SOIL—INTERFACE OF AIR, MINERALS, WATER, AND LIFE

The relative proportions of air, water, mineral matter, and organic matter greatly influence the behavior and productivity of soils. In a soil, these four components are mixed in complex patterns. Figure 1.21 shows the approximate proportions (by volume) of the components found in a **loam** surface soil in good condition for plant growth. Although a handful of soil may at first seem to be a solid thing, it should be noted that only about half the soil volume consists of solid material (mineral and organic); the other half consists of pore spaces filled with air or water. Of the solid material, typically most is mineral matter derived from the rocks of the Earth's crust. Only about 5% of the *volume* in this ideal soil consists of organic matter. Since it is far less dense than mineral matter, the organic matter accounts for only about 2% of the *weight* of this soil. However, the influence of the organic component on soil properties is often far greater than these small proportions would suggest.

The spaces between the particles of solid material are just as important to the nature of a soil as are the particles themselves. Soils with much more than 50% of their volume in solids are likely to be too compacted for good plant growth. It is in these pore spaces that air and water circulate, roots grow, and microscopic creatures live. Plant roots need both air and water. In an optimum condition for most plants, the pore space will be divided roughly equally among the two, with 25% of the soil volume consisting of water and 25% consisting of air. If there is much more water than this, the soil will be waterlogged. If much less water is present, plants will suffer from drought. The relative proportions of water and air fluctuate as water is added or lost. Compared to surface soil layers, subsoils tend to contain less organic matter, less total pore space, and a larger proportion of its pore space is made up of small pores (*micropores*), which tend to be filled with water rather than with air.

1.13 WHAT ARE THE MINERAL (INORGANIC) CONSTITUENTS OF SOILS?

Except in organic soils, most of the soil's solid framework consists of **mineral**[4] particles. The larger soil particles (stones, gravel, and coarse sands) are generally rock fragments consisting of several different minerals. Smaller particles tend to be made of a single mineral.

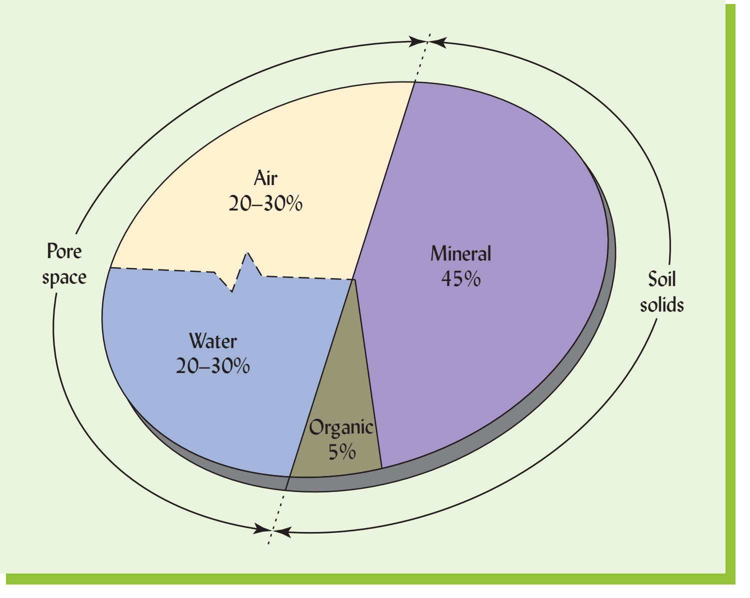


Figure 1.21 *Volume composition of a loam surface soil when conditions are good for plant growth. The broken line between water and air indicates that the proportions of these two components fluctuate as the soil becomes wetter or drier. Nonetheless, a nearly equal proportion of air and water is generally ideal for plant growth.*

[4]The word *mineral* is used in soil science in three ways: (1) as a general adjective to describe inorganic materials derived from rocks; (2) as a specific noun to refer to distinct minerals found in nature such as quartz and feldspars (see Chapter 2 for detailed discussions of soil-forming minerals and the rocks in which they are found); and (3) as an adjective to describe chemical elements, such as nitrogen and phosphorus, in their inorganic state in contrast to their occurrence as part of organic compounds.

Excluding, for the moment, the larger rock fragments such as stones and gravel, soil particles range in size over four orders of magnitude: from 2.0 millimeters (mm) to smaller than 0.0002 mm in diameter (Table 1.2). **Sand** particles are large enough (2.0–0.05 mm) to be seen by the naked eye and feel gritty when rubbed between the fingers. Sand particles do not adhere to one another; therefore, sands do not feel sticky. **Silt** particles (0.05–0.002 mm) are too small to be seen without a microscope or to be felt individually, so silt feels smooth but not sticky, even when wet. **Clay** particles are the smallest mineral particles (<0.002 mm) and adhere together to form a sticky mass when wet and hard clods when dry. The smaller particles (<0.001 mm) of clay (and similar-sized organic particles) have **colloidal**[5] properties and can be seen only with the aid of an electron microscope. Because of their extremely small size, colloidal particles possess a tremendous amount of surface area per unit of mass. The surfaces of soil colloids (both mineral and organic) exhibit electromagnetic charges that attract positive and negative ions as well as water, making this fraction of the soil the most chemically and physically active (see Chapter 8).

Soil Texture

The proportion of particles in these different size ranges is described by **soil texture**. Terms such as *sandy loam*, *silty clay*, and *clay loam* are used to identify the soil texture. Texture has a profound influence on many soil properties, and it affects the suitability of a soil for most uses. To understand the degree to which soil properties can be influenced by texture, imagine sunbathing first on a sandy beach (loose sand) and then on a clayey beach (sticky mud). The difference in these two experiences would be due largely to the properties described in Table 1.2.

To anticipate the effect of clay on the way a soil will behave, it is necessary to know the *kinds* of clays as well as the *amount* present. As home builders and highway engineers know all too well, certain clayey soils, such as those high in smectite clays, make very unstable material on which to build because they swell when wet and shrink when dry. This shrink–swell action can easily crack foundations and cause retaining walls to collapse. These clays also become extremely sticky and difficult to work with when they are wet. Other types of clays, formed under different conditions, can be very stable and easy to work with. Learning about the different types of clay minerals will help us understand many of the physical and chemical differences among soils in various parts of the world (see Box 1.4).

Table 1.2
Some General Properties of the Three Major Size Classes of Inorganic Soil Particles

	Property	Sand	Silt	Clay
1.	Range of particle diameters in millimeters	2.0–0.05	0.05–0.002	Smaller than 0.002
2.	Means of observation	Naked eye	Microscope	Electron microscope
3.	Dominant minerals	Primary	Primary and secondary	Secondary
4.	Attraction of particles for each other	Low	Medium	High
5.	Attraction of particles for water	Low	Medium	High
6.	Ability to hold chemicals and nutrients in plant-available form	Very low	Low	High
7.	Consistency when wet	Loose, gritty	Smooth	Sticky, malleable
8.	Consistency when dry	Very loose, gritty	Powdery, some clods	Hard clods

[5]Colloidal systems are two-phase systems in which very small particles of one substance are dispersed in a medium of a different substance. Clay and organic soil particles smaller than about 0.001 mm (1 micrometer, µm) in diameter are generally considered to be colloidal in size. Milk and blood are other examples of colloidal systems in which very small solid particles are dispersed in a liquid medium.

BOX 1.4
OBSERVING SOILS IN DAILY LIFE

Your study of soils can be enriched if you make an effort to become aware of the many daily encounters with soils and their influences that go unnoticed by most people. When you dig a hole to plant a tree or set a fence post, note the different layers encountered, and note how the soil from each layer looks and feels. If you pass a construction site, take a moment to observe the horizons exposed by the excavations. An airplane trip is a great opportunity to observe how soils vary across landscapes and climatic zones. If you are flying during daylight hours, ask for a window seat on the side away from the sun. Look for the shapes or divisions between individual soils in plowed fields if you are flying over agricultural land near the beginning of the growing season (Figure 1.22).

Soils can give you clues to understanding the natural processes going on around you. Down by the stream, use a magnifying glass to examine the sand deposited on the banks or bottom. It may contain minerals not found in local rocks and soils but originating many kilometers upstream. When you wash your car, see if the mud clinging to the tires and fenders is of a different color or consistency than the soils near your home. Does the "dirt" on your car tell you where you have been driving? Other examples of soil hints can be found even closer to home. The next time you bring home celery or leaf lettuce from the supermarket, look carefully for bits of soil clinging to the bottom of the stalk or leaves (Figure 1.23). Rub the soil between your thumb and fingers. Smooth, very black soil may indicate that the lettuce was grown in mucky soils, such as those in New York State or southern Florida. Light brown, smooth-feeling soil with only a very fine grittiness is more typical of California-grown produce, whereas light-colored, gritty soil is common on produce from the sandy coastal soils (such as southern Georgia–northern Florida vegetable-growing region). In a bag of dry beans, you may come across a few lumps of soil that escaped removal in the cleaning process because of being the same size as the beans. Often this soil is dark-colored and very sticky, coming from the "thumb" area of Michigan, where a large portion of the U.S. dry bean crop is grown on clayey lake-bed soils.

Opportunities to observe soils in daily life range from the remote and large-scale to the close-up and intimate. As you learn more about soils, you will undoubtedly be able to see more examples of their influence in your surroundings.

Figure 1.22 *The light- and dark-colored soil bodies, as seen from an airliner flying over central Texas, reflect differences in drainage, erosion, and topography in the landscape.* (Photo courtesy of Ray R. Weil)

Figure 1.23 *Although this celery was purchased in a Virginia grocery store in early fall, the black, mucky soil clinging to the base of the stalk indicates that it was grown on organic soils, probably in New York State.* (Photo courtesy of Ray R. Weil)

Soil Minerals

Minerals that have persisted with little change in composition since they were extruded in molten lava (e.g., quartz, micas, and feldspars) are known as **primary minerals**. They are prominent in the sand and silt fractions of soils and contain many of the nutrient elements needed by plants. Other minerals, such as silicate clays and iron oxides, were formed by the breakdown and weathering of less resistant minerals as soil formation progressed. These minerals are called **secondary minerals** and tend to dominate the clay and, in some cases, silt fractions. Soil mineralogical signatures are one of the clues used by forensic soil scientists to locate crime victims or establish guilt by matching soil clinging to shoes, tires, tools, or under fingernails with soil from a crime scene (Figure 1.24).

Figure 1.24 *Soil can be useful in solving crime mysteries and is often placed in evidence in court proceedings. The mud clinging to these boots* (center) *was used to prove the innocence of a man accused of robbery and breaking into a house. In this case the type of sand grains found in the mud from the boots was typical of quartz-rich soils* (left)*, which occurred at the job site of the accused but not anywhere near the crime site, which instead had soils with mica-rich sands* (right)*. The largest sand grains in both photos are about 1 mm in diameter.*
(Photos courtesy of Ray R. Weil)

Soil Structure

Sand, silt, and clay particles can be thought of as the building blocks from which soil is constructed. **Soil structure** describes the way these building blocks are associated together in aggregates of various sizes and shapes (see, e.g., the nature of the soil "clumps" in Figure 1.18, *right*). Soil structure (the way particles are arranged together) is just as important as soil texture (the relative amounts of different sizes of particles) in governing how water and air move in soils. Both structure and texture fundamentally influence many processes in soil, including the growth of plant roots.

1.14 THE NATURE OF SOIL ORGANIC MATTER

Soil organic matter consists of a wide range of organic (carbonaceous) substances, including living organisms (the soil ***biomass***), carbonaceous remains of organisms that once occupied the soil, and organic compounds produced by current and past metabolism in the soil. Over time, organic matter is destroyed by microbial respiration and its carbon is lost from the soil as carbon dioxide. Because of such losses, repeated additions of new plant and/or animal residues are necessary to maintain soil organic matter.

Under conditions that favor plant production more than microbial decay, large quantities of atmospheric carbon dioxide used by plants in photosynthesis are sequestered in the abundant plant tissues that eventually become part of the soil organic matter. Since carbon dioxide is a major greenhouse gas whose increase in the atmosphere is warming Earth's climate, the balance between accumulation of soil organic matter and its loss through microbial respiration has global implications. In fact, more carbon is stored in the world's soils than in the world's plant biomass and atmosphere combined.

Even so, organic matter comprises only a small fraction of the mass of a typical soil. By weight, typical well-drained mineral surface soils contain from 1 to 6% organic matter. The organic matter content of subsoils is even smaller. However, the influence of organic matter on soil properties, and consequently on plant growth, is far greater than the low percentage would indicate (see also Chapter 12).

Organic matter binds mineral particles into a granular soil structure that is largely responsible for the loose, easily managed condition of productive soils. Part of the soil organic matter that is especially effective in stabilizing these granules consists of certain glue-like substances produced by various soil organisms, including plant roots (Figure 1.25).

Organic matter also increases the amount of water a soil can hold and the proportion of water available for plant growth (Figure 1.26). In addition, organic matter is a major source of the plant nutrients nitrogen, phosphorus, and sulfur. As soil organic matter decays, these nutrient elements, which are present in organic combinations, are released as soluble ions that

Figure 1.25 *Abundant organic matter, including plant roots, helps create physical conditions favorable for the growth of higher plants as well as microbes* (left). *In contrast, soils low in organic matter, especially if they are high in silt and clay, are often cloddy* (right) *and not suitable for optimum plant growth.* (Photo courtesy of Ray R. Weil)

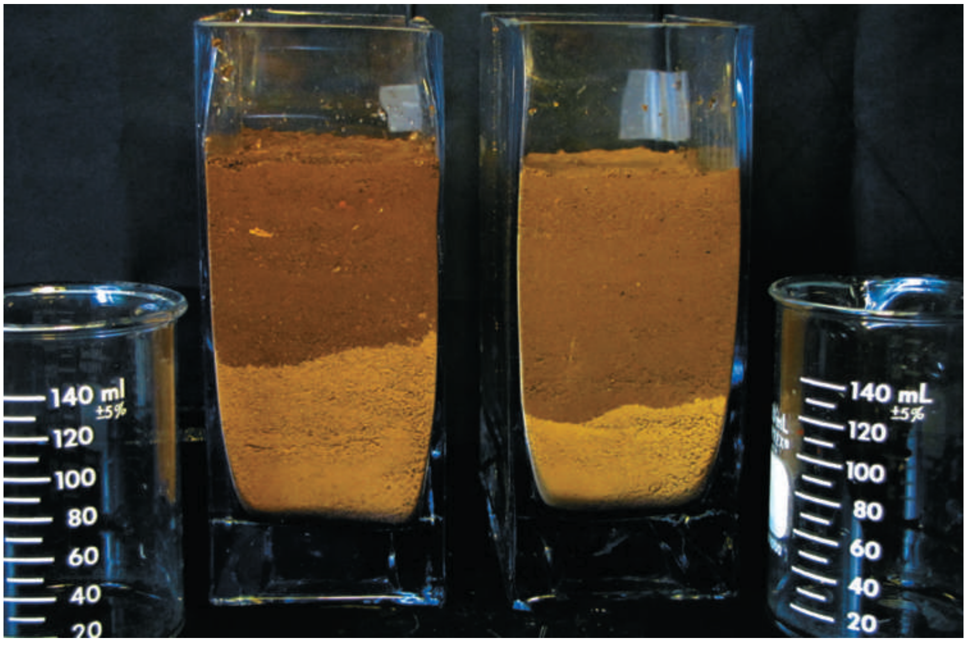


Figure 1.26 *Soils higher in organic matter are darker in color and have greater water-holding capacities than soils low in organic matter. The soil in each container has the same texture, but the one on the right has been depleted of much of its organic matter. The same amount of water was applied to each container. As the photo shows, the depth of water penetration was less in the high organic matter soil* (left) *because of its greater water-holding capacity. It required a greater volume of the low organic matter soil to hold the same amount of water.* (Photo courtesy of Ray R. Weil)

can be taken up by plant roots. Finally, organic matter, including plant and animal residues, is the main food that supplies carbon and energy to soil organisms. Without it, biochemical activity so essential for ecosystem functioning would come to a near standstill.

Humus, usually black or brown in color, is a collection of organic compounds that accumulate in soil when partially broken down plant and animal residues are protected from complete decay by various factors in the soil environment. Like clay, much of the soil's humus is colloidal in size and exhibits highly charged surfaces. Both humus and clay act as contact bridges between larger soil particles; thus, both play an important role in the formation of soil structure. The surface charges of humus, like those of clay, attract and hold both nutrient ions and water molecules. However, gram for gram, the capacity of humus to hold nutrients and water is far greater than that of clay. Unlike clay, humus may contain components that can make micronutrients more easily used by plants and may even cause hormone-like stimulation of certain plant processes. All in all, small amounts of humus remarkably increase the soil's capacity to promote plant growth.

1.15 SOIL WATER—DYNAMIC AND COMPLEX

The soil moisture regime, often reflective of climatic factors, is a major determinant of the productivity of terrestrial ecosystems, including agricultural systems. Movement of water, and substances dissolved in it, through the soil profile impacts both the quality and quantity of local and regional water resources. Water moving through the regolith is also a major driving force in soil formation (see Box 2.1).

Two main factors help explain why **soil water** is different from our everyday concept of, say, drinking water in a glass:

1. Water is held within soil pores where the attraction between water and the surfaces of soil particles greatly restricts the ability of water to flow as it would flow in a drinking glass.
2. Because soil water is never pure water, but contains hundreds of dissolved organic and inorganic substances, it may be more accurately called the ***soil solution***. An important function of the soil solution is to serve as a constantly replenished, dilute nutrient solution bringing dissolved nutrient elements (e.g., calcium, potassium, nitrogen, and phosphorus) to plant roots.

When the soil moisture content is optimal for plant growth (Figure 1.21), the water in the large- and intermediate-sized pores can move about in the soil and can easily be used by plants. The plant roots, however, remove water from the largest pores first. Soon the larger pores hold only air, and the remaining water is found only in the intermediate- and smallest-sized pores. The water in the intermediate-sized pores can still move toward plant roots and be taken up by them. However, the water in the smallest pores is so close to solid particles that it may be so strongly held that plant roots cannot pull it away. Consequently, not all soil water is *available* to plants. Depending on the soil, one-sixth to one-half of the water may remain in the soil after plants have wilted or died for lack of moisture.

Soil Solution

The soil solution contains small but significant quantities of soluble organic and inorganic substances, including the plant nutrients listed in Table 1.1. The soil solids, particularly the fine organic and inorganic colloidal particles (clay and humus), release nutrient elements to the soil solution from which they are taken up by plant roots. The soil solution tends to resist changes in its composition even when compounds are added or removed from the soil. This ability to resist change is termed the soil **buffering capacity** and is dependent on many chemical and biological reactions, including the attraction and release of substances by colloidal particles (see Chapter 8).

Many chemical and biological reactions are controlled by the relative amounts of acidity caused by a dominance of hydrogen ions (H^+) and alkalinity caused by a dominance of hydroxyl ions (OH^-) in the soil solution (Figure 1.27). The **pH** is a logarithmic scale used to express the degree of soil acidity or alkalinity (see Chapter 9, especially Box 9.1 and Figure 9.2). The pH is

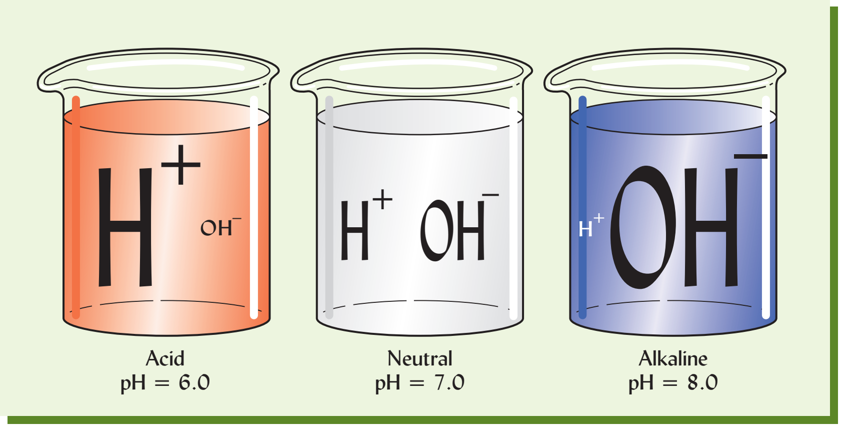


Figure 1.27 *Diagram representing acidity, neutrality, and alkalinity. At neutrality (pH = 7), H^+ and OH^- ions are present in equal numbers. At pH 6, there are 10 times more H^+ ions than at pH 7, while the number of OH^- ions is 10 times less than at pH7. Thus at pH 6 H^+ outnumber OH^- ions 100 to 1 and the solution is therefore acid. Conversely, at pH 8 the OH^- are 100 times more plentiful than the H^+ and the solution is alkaline. This mutually inverse relationship between H^+ and OH^- ions must be kept in mind whenever pH data are considered.* (Diagram courtesy of N. C. Brady)

considered a master variable that influences most chemical processes in the soil and is of great significance to nearly all aspects of soil science.

1.16 SOIL AIR: A CHANGING MIXTURE OF GASES

Think how stuffy the air would become if the ventilation ducts of a windowless classroom became clogged. If we think of the network of soil pores as the ventilation system of the soil connecting airspaces to the atmosphere, we can understand that when pores are filled with water the ventilation system becomes clogged. Because oxygen could neither enter the room nor carbon dioxide leave it, the air in the room would soon become depleted of oxygen and enriched in carbon dioxide and water vapor by the respiration (breathing) of the people in it. In an air-filled soil pore surrounded by water-filled smaller pores, the metabolic activities of plant roots and microorganisms have a similar effect.

Therefore, soil air differs from atmospheric air in several respects. First, the composition of soil air varies greatly from place to place in the soil. In local pockets, some gases are consumed by plant roots and by microbial reactions, and others are released, thereby greatly modifying the composition of the soil air. Second, soil air generally has a higher moisture content than the atmosphere; the relative humidity of soil air approaches 100% unless the soil is very dry. Third, the content of carbon dioxide (CO_2) is usually much higher, and that of oxygen (O_2) lower, than contents of these gases found in the atmosphere. Carbon dioxide in soil air is often several hundred times more concentrated than the 0.035% commonly found in the atmosphere. Oxygen decreases accordingly and, in extreme cases, may be 5–10%, or even less, compared to about 20% for atmospheric air. In extreme cases, lack of oxygen both in the soil air and dissolved in the soil water may fundamentally alter the chemical reactions that take place in the soil solution. This is of particular importance to understanding the functions of wetland soils.

The amount and composition of air in a soil are determined to a large degree by the water content of the soil. When water enters the soil, it displaces air from some of the pores; the air content of a soil is therefore inversely related to its water content. As the soil drains from a heavy rain or irrigation, large pores are the first to be filled with air, followed by medium-sized pores, and finally the small pores, as water is removed by evaporation and plant use. This explains the tendency for soils with a high proportion of tiny pores to be poorly aerated.

1.17 HOW DO SOIL COMPONENTS INTERACT TO SUPPLY NUTRIENTS TO PLANTS?

As you read our discussion of each of the four major soil components, you may have noticed that the impact of one component on soil properties is seldom expressed independently from that of the others. Rather, the four components interact with each other to determine the nature of a soil. Thus, soil moisture, which directly meets the needs of plants for water, simultaneously controls much of the air and nutrient supply to the plant roots. The mineral particles, especially the finest ones, attract soil water, thus determining its movement and availability to plants. Likewise, organic matter, because of its physical binding power, influences the arrangement of the mineral particles into clusters and, in so doing, increases the number of large soil pores, thereby influencing the water and air relationships.

Essential Element Availability

Perhaps the most important interactive process involving the four soil components is the provision of essential nutrient elements to plants. Plants absorb essential nutrients, along with water, directly from one of these components: the soil solution. However, the amount of essential nutrients in the soil solution at any one time is sufficient to supply the needs of growing vegetation for only a few hours or days. Consequently, the soil solution nutrient levels must be constantly replenished from the inorganic or organic parts of the soil and from fertilizers or manures added to agricultural soils.

By a series of chemical and biochemical processes, nutrients are released from these solid forms to replenish those in the soil solution. For example, the tiniest colloidal-sized particles—both clay and humus—exhibit negative and positive charges. These charges tend to

Table 1.3
QUANTITIES OF SIX ESSENTIAL ELEMENTS FOUND IN UPPER 15 CM OF REPRESENTATIVE SOILS IN TEMPERATE REGIONS

	Humid Region Soil			Arid Region Soil		
Essential element	In solid framework, kg/ha	Exchangeable, kg/ha	In soil solution, kg/ha	In solid framework, kg/ha	Exchangeable, kg/ha	In soil solution, kg/ha
Ca	8,000	2,250	60–120	20,000	5,625	140–280
Mg	6,000	450	10–20	14,000	900	25–40
K	38,000	190	10–30	45,000	250	15–40
P	900	—	0.05–0.15	1,600	—	0.1–0.2
S	700	—	2–10	1,800	—	6–30
N	3,500	—	7–25	2,500	—	5–20

attract or **adsorb**[6] oppositely charged ions from the soil solution and hold them as **exchangeable ions**. Through ion exchange, elements such as Ca^{2+} and K^{+} are released from this state of electrostatic adsorption on colloidal surfaces and escape into the soil solution where they can be readily taken up (absorbed) by plant roots. Some scientists consider that this ion exchange process is among the most important of chemical reactions in nature.

Nutrient ions are also released to the soil solution as soil microorganisms decompose organic tissues. Plant roots can readily absorb all of these nutrients from the soil solution, provided there is enough O_2 in the soil air to support root metabolism.

Most soils contain large amounts of plant nutrients relative to the annual needs of growing vegetation. However, the bulk of most nutrient elements is held in the structural framework of primary and secondary minerals and organic matter. Only a small fraction of the nutrient content of a soil is present in forms that are readily available to plants. Table 1.3 will give you some idea of the quantities of various essential elements present in different forms in typical soils of humid and arid regions.

Figure 1.28 illustrates how the two solid soil components interact with the liquid component (soil solution) to provide essential elements to plants. Plant roots do not ingest soil particles, no matter how fine, but are able to absorb only nutrients that are dissolved in the soil solution. Because elements in the coarser soil framework of the soil are only slowly released into the soil solution over long periods of time, the bulk of most nutrients in a soil is not readily available for plant use. Nutrient elements in the framework of colloid particles are somewhat more readily available to plants, as these particles break down much faster because of their greater surface area. Thus, the structural framework is the major storehouse and, to some extent, a significant source of essential elements in many soils.

The distribution of nutrients among the various components of a fertile soil, as illustrated in Figure 1.28, may be likened to the distribution of financial assets in the portfolio of a wealthy individual. Nutrients readily available for plant use would be analogous to cash in the individual's pocket. A millionaire would likely keep most of his or her assets in long-term investments such as real estate or bonds (the coarse fraction solid framework), while investing a smaller amount in short-term stocks and bonds (colloidal framework). For more immediate use, an even smaller amount might be kept in a checking account linked to an automated teller machine (exchangeable nutrients), while a tiny fraction of the overall wealth might be carried to spend as currency and coins (nutrients in the soil solution). As the cash is used up, the supply is replenished by making a withdrawal from the ATM. The checking account, in turn, is replenished occasionally by the sale of long-term investments. It is possible for wealthy persons to run short of coins for a vending

[6]*Adsorption* refers to the attraction of ions to the surface of particles, in contrast to *absorption*, the process by which ions are taken *into* plant roots. The adsorbed ions are exchangeable with ions in the soil solution.

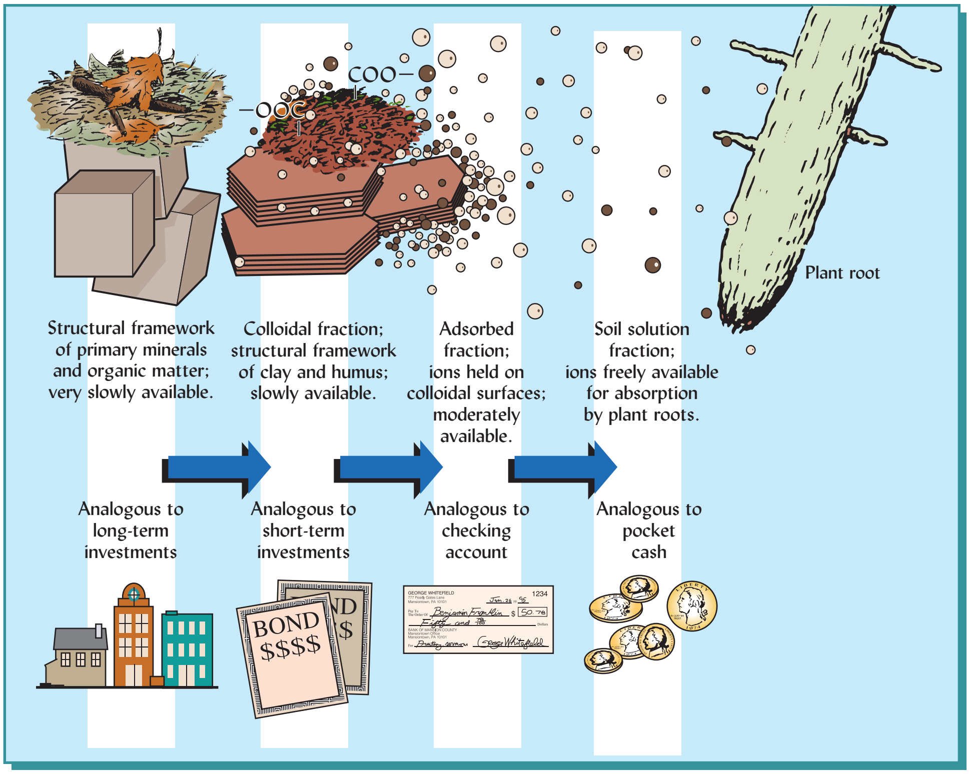


Figure 1.28 *Nutrient elements exist in soils in various forms characterized by different accessibility to plant roots. The bulk of the nutrients is locked up in the structural framework of primary minerals, organic matter, clay, and humus. A smaller proportion of each nutrient is adsorbed in a swarm of ions near the surfaces of soil colloids (clay and organic matter). From the swarm of adsorbed ions, a still smaller amount is released into the bulk soil solution, where uptake by plant roots can take place. The lower diagram considers the analogy between financial assets and nutrient assets.* (Diagram courtesy of Ray R. Weil)

machine even though they may own a great deal of valuable real estate. In an analogous way, plants may use up the readily available supply of a nutrient even though the total supply of that nutrient in the soil is very large. Luckily, in a fertile soil, the process described in Figure 1.28 can help replenish the soil solution as quickly as plant roots remove essential elements.

1.18 HOW DO PLANT ROOTS OBTAIN NUTRIENTS?

To be taken up by a plant, the nutrient element must be in a soluble form and must be located *at the root surface*. Often, parts of a root are in such intimate contact with soil particles (see Figure 1.29) that a direct exchange may take place between nutrient ions adsorbed on the surface of soil colloids and H^+ ions from the surface of root cell walls. In any case, the supply of nutrients in contact with the root will soon be depleted. So how can a root obtain additional supplies once the nutrient ions at the root surface have all been taken up into the root? There are three basic mechanisms by which the concentration of nutrient ions at the root surface is maintained (Figure 1.30).

First, **root interception** comes into play as roots continually grow into new, undepleted soil. Root exploration in search of nutrients is much enhanced by thin root cell extensions called **root hairs**. In fact, root hair growth was recently discovered to be controlled by a regulatory plant gene that is "turned on" by low nutrient conditions. Even with root hairs extending into tiny water-filled soil pores where nutrients may be dissolved, for the most part, nutrient ions must still travel some distance in the soil solution to reach the root surface. This movement can take place by **mass flow**, as when dissolved nutrients are carried along with the flowing soil water toward a root that is actively drawing water from the soil. In this type of movement, the nutrient ions are somewhat analogous to leaves floating down a stream. On the other hand, plants can continue to take up nutrients even at night, when little, if any, water is absorbed into the roots. Nutrient ions continually move by **diffusion** from areas of greater concentration toward the nutrient-depleted areas of lower concentration around the root surface.

In the diffusion process, the random movements of ions in all directions causes a *net* movement from areas of high concentration to areas of lower concentrations, independent of any mass flow of the water in which the ions are dissolved. Factors such as soil compaction, cold temperatures, and low soil moisture content, which reduce root interception, mass flow, or diffusion, can result in poor nutrient uptake by plants even in soils with adequate supplies

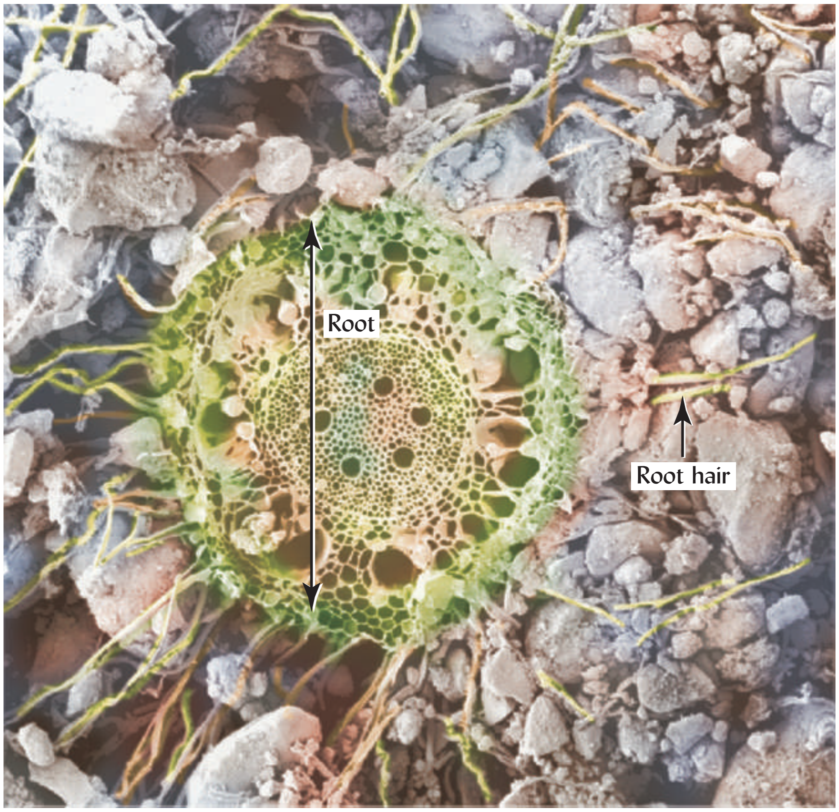


Figure 1.29 *Cross section of a barley root growing in field soil. Note the intimate contact between the root and the soil, made more so by the long, thin root hairs that permeate the nearby soil and bind it to the root. The root itself is about 0.3 mm in diameter.* (Cryo scanning electron micrograph courtesy of Margaret McCully, CSIRO, Plant Industry, Canberra, Australia)

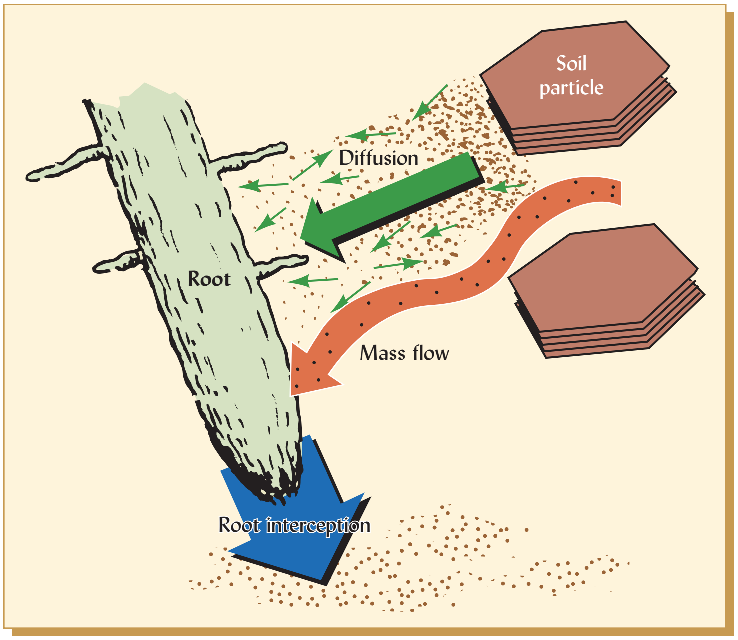


Figure 1.30 *Three principal mechanisms by which nutrient ions dissolved in the soil solution come into contact with plant roots. All three mechanisms may operate simultaneously, but one mechanism or another may be most important for a particular nutrient. For example, in the case of calcium, which is generally plentiful in the soil solution, mass flow alone can usually bring sufficient amounts to the root surface. However, in the case of phosphorus, diffusion is needed to supplement mass flow because the soil solution is very low in this element in comparison to the amounts needed by plants.* (Diagram courtesy of Ray R. Weil)

of soluble nutrients. Furthermore, the availability of nutrients for uptake can also be negatively or positively influenced by the activities of microorganisms that thrive in the immediate vicinity of roots. Maintaining the supply of available nutrients at the plant root surface is thus a process that involves complex interactions among different soil components.

It should be noted that the plant membrane separating the inside of the root cell from the soil solution is permeable to dissolved ions only under special circumstances. Plants do not merely take up, by mass flow, those nutrients that happen to be in the water that roots are removing from the soil. Nor do dissolved nutrient ions brought to the root's outer surface by mass flow or diffusion cross the root cell membrane and enter the root passively by diffusion.

On the contrary, a nutrient is normally taken up into the plant root cell only by reacting with specific chemical binding sites on large protein molecules embedded in the root membrane. These proteins form hydrophilic channels across an otherwise hydrophobic lipid (fatty) membrane. Energy from metabolism in the root cell is used to activate this carrier protein so that it will pass the nutrient ion across the cell membrane and release it into the cell interior. This carrier mechanism allows the plant to accumulate concentrations of a nutrient inside the root cell that far exceed that nutrient's concentration in the soil solution. Because different nutrients are taken up by specific types of protein molecules, the plant is able to exert some control over how much and in what relative proportions essential elements are taken up.

Nutrient uptake being an active metabolic process, conditions that inhibit root metabolism may also inhibit nutrient uptake. Examples of such conditions include excessive soil water content or soil compaction resulting in poor soil aeration, excessively hot or cold soil temperatures, and aboveground conditions that result in low translocation of sugars to plant roots. We can see that plant nutrition involves biological, physical, and chemical processes and interactions among many different components of soils and the environment.

1.19 SOIL HEALTH, DEGRADATION, AND RESILIENCE

Soil is a basic resource underpinning all terrestrial ecosystems. Managed carefully, soils are a *reusable* resource, but in the scale of human lifetimes they cannot be considered a *renewable* resource. As we shall see in the next chapter, most soil profiles are thousands of years in the making. In all regions of the world, human activities are destroying some soils far faster than nature can rebuild them. Growing numbers of people are demanding more and more ecosystem services from the Earth's fixed amount of land. This situation presents soil scientists and humanity with a number of grand challenges that must be met if human civilization and nature are to be sustained side by side (Table 1.4).

In most parts of the world, nearly all of the soils best suited for growing crops are already being farmed. Therefore, as each year brings millions more people to feed, the amount of cropland per person continuously declines. In addition, many of the world's major cities were originally located where excellent soils supported thriving agricultural communities. Without policies to protect farmland, many of the very best soils for farming are lost to suburban development as these cities expand.

Finding more land on which to grow food is not easy. Most additional land brought under cultivation comes at the cost of clearing natural forests, savannas, and grasslands. Images of the Earth made from orbiting satellites show the resulting decline in land covered by forests and other natural ecosystems. Thus, as the human population struggles to feed itself, wildlife populations are deprived of vital habitat, and overall biodiversity suffers. Efforts to reduce and even reverse human population growth must be accelerated if our grandchildren are to inherit a livable world. In the meantime, if there is to be space for both people and wildlife, the best of our existing farmland soils will require improved and more intensive management. While soils completely washed away by erosion or excavated and paved over by urban sprawl are permanently lost, many more soils are degraded in quality rather than totally destroyed.

Soil Quality and Health

People who work with the land and depend on soils to perform critical functions want to improve and maintain **soil health**. They recognize that soils are living systems with highly complex and diverse communities of organisms. In their optimal state, these organisms work together to function in a self-regulating and perpetuating manner (Chapter 20). Healthy soils function more efficiently with less need for expensive human interventions and inputs than unhealthy, degraded soils. **Soil quality** is a measure of the ability of a soil to carry out particular ecological functions, such as those described in Sections 1.2–1.7. Soil quality reflects a combination of *chemical*, *physical*, and *biological* properties. Some of these properties are relatively unchangeable, inherent properties that help define a particular type of soil. Soil texture and mineral makeup (Section 1.13) are examples. Other soil properties, such as structure (Section 1.13) and organic matter content (Section 1.14), can be significantly changed by management. These more changeable soil properties can indicate the status of a soil's quality relative

Table 1.4
Grand Soil Science Challenges for 2050

No.	Topic Area	Grand Challenge
1	Food	How can we feed 2 billion *more* people than today without harming our soils or the broader environment?
2	Nutrients	How do we preserve and enhance the fertility of our soils, conserve scarce nutrient resources and also export nutrients from farms to cities in ever bigger harvests?
3	Fresh water	How can we manage our soils to use dwindling water supplies more efficiently and wisely while managing soils to protect our waters from pollution?
4	Energy	How can we sustainably manage our lands to contribute to energy supplies by integrating biochar use and producing biofuel feedstocks?
5	Climate change	How can we manage soils to mitigate climate change by reducing greenhouse gases while also adapting to climate change by protecting soil productivity and resilience?
6	Biodiversity	How can we better understand and enhance the biotic communities within and on the soil to create more resilient and productive ecosystems and utilize the diverse gene pool?
7	Recycling "wastes"	How can we better use soils as biogeochemical reactors to avoid contamination, detoxify contaminants, and maintain soil productivity?
8	Global perspective	How can we develop a global perspective that still permits us to optimize management of local places, wherever they may be?

Modified from Janzen et al. (2011)

to its potential, in much the same way that water turbidity or oxygen content indicates the water-quality status of a river.

Soil Degradation and Resilience

Mismanagement of forests, farms, and rangeland causes widespread degradation of soil quality by erosion that removes the topsoil, little by little (see Chapter 17). Another widespread cause of soil degradation is the accumulation of salts in improperly irrigated soils in arid regions (see Chapter 10). When people cultivate soils and harvest the crops without returning organic residues and mineral nutrients, the soil's supply of organic matter and nutrients becomes depleted (see Chapter 12). Such depletion is particularly widespread in sub-Saharan Africa, where degrading soil quality is reflected in diminished capacity to produce food (see Chapter 20). Contamination of a soil with toxic substances from industrial processes or chemical spills can degrade its capacity to provide habitat for soil organisms, to grow plants that are safe to eat, or to safely recharge ground and surface waters (see Chapter 18). Degradation of soil quality by pollution is usually localized, but the environmental impacts and costs involved are very large.

While protecting soil quality must be the first priority, it is often necessary to attempt to restore the quality of soils that have already been degraded. Some soils have sufficient **resilience** to recover from minor degradation if left to regenerate on their own. In other cases, more effort is required to restore degraded soils (see Chapter 17). Organic and inorganic amendments may have to be applied, vegetation may have to be planted, physical alterations by tillage or grading may have to be made, or contaminants may have to be removed. As societies around the world assess the damage already done to their natural and agricultural ecosystems, the science of **restoration ecology** has rapidly evolved to guide managers in restoring plant and animal communities to their former levels of diversity and productivity. The job of **soil restoration**, an essential part of these efforts, requires in-depth knowledge of all aspects of the soil system.

1.20 CONCLUSIONS

The Earth's soil is comprised of numerous soil individuals, each of which is a three-dimensional natural body in the landscape. Each individual soil is characterized by a unique set of properties and soil horizons as expressed in its profile. The nature of the soil layers seen in a particular profile is closely related to the nature of the environmental conditions at a site.

Soils perform six broad ecological functions: they act as the principal medium for plant growth, regulate water supplies, modify the atmosphere, recycle raw materials and waste products, provide habitat for many kinds of organisms, and serve as a major engineering medium for human-built structures. Soil is thus a major ecosystem in its own right. The soils of the world are extremely diverse, each type of soil being characterized by a unique set of soil horizons. A typical surface soil in good condition for plant growth consists of about half solid material (mostly mineral, but with a crucial organic component, too) and half pore spaces filled with varying proportions of water and air. These components interact to influence a myriad of complex soil functions, a good understanding of which is essential for wise management of our terrestrial resources.

If we take the time to learn the language of the land, the soil will speak to us.

STUDY QUESTIONS

1. As a society, is our reliance on soils likely to increase or decrease in the decades ahead? Explain.
2. Discuss how *a soil*, a natural body, differs from *soil*, a material that is used in building a roadbed.
3. What are the six main roles of soil in an ecosystem? For each of these ecological roles, suggest one way in which interactions occur with another of the six roles.
4. Think back over your activities during the past week. List as many incidents as you can in which you came into direct or indirect contact with soil.
5. Figure 1.21 shows the volume composition of a loam surface soil in ideal condition for plant growth. To help you understand the relationships among the four components, redraw this pie chart to represent what the situation might be after the soil has been compacted by heavy traffic. Then draw another pie chart to show how the four components of the original ideal soil would be related on a mass (weight) basis rather than on a volume basis.
6. Explain in your own words how the soil's nutrient supply is held in different forms, much the way that a person's financial assets might be held in different forms.
7. List the essential nutrient elements that plants derive mainly from the soil.
8. Are all elements contained in plants essential nutrients? Explain.
9. Define these terms: *soil texture*, *soil structure*, *soil pH*, *humus*, *soil profile*, *B horizon*, *soil quality*, *solum*, and *saprolite*.
10. Describe four processes that commonly lead to degradation of soil quality.
11. Compare the pedological and edaphological approaches to the study of soils. Which is more closely aligned with geology and which with ecology?
12. Which of the *grand challenges* listed in Table 1.4 is most exciting and inspiring to you, and why?

REFERENCES

Abrahams, P. W. 2005. "Geophagy and the involuntary ingestion of soil," pp. 435–457, in O. Selinus (ed.), *Essentials of Medical Geology*. Elsevier, The Hauge.

Abrahams, P. W. 2012. "Involuntary soil ingestion and geophagia: A source and sink of mineral nutrients and potentially harmful elements to consumers of earth materials," *Appl Geochem*., **27**:in press.

Alloway, B. J., and R. D. Graham. 2008. "Micronutrient deficiencies in crops and their global significance," pp. 41–61, in B. J. Alloway (ed.), *Micronutrient Deficiencies in Global Crop Production*. Springer, Netherlands.

Epstein, E., and A. J. Bloom. 2005. *Mineral Nutrition of Plants: Principles and Perspectives*. 2nd ed. Sinauer Associates, Sunderland, MA. 400 p.

Fisher, M. 2012. "Investigating the earth's critical zone," *CSA News*, **57**(1):5–9.

Frager, S. Z., C. J. Chrisman, R. Shakked, and A. Casadevall. 2010. "Paramecium species ingest and kill the cells of the human pathogenic fungus cryptococcus neoformans," *Med Mycol*., **48**:775–779.

Griffin, D. W. 2007. "Atmospheric movement of microorganisms in clouds of desert dust and implications for human health," *Clin Microbiol Rev*., **20**:459–477.

Janzen, H. H., P. E. Fixen, A. J. Franzluebbers, J. Hattey, R. C. Izaurralde, Q. M. Ketterings, D. A. Lobb, and W. H. Schlesinger. 2011. "Global prospects rooted in soil science," *Soil Sci Soc Am J*., **75**:1–8.

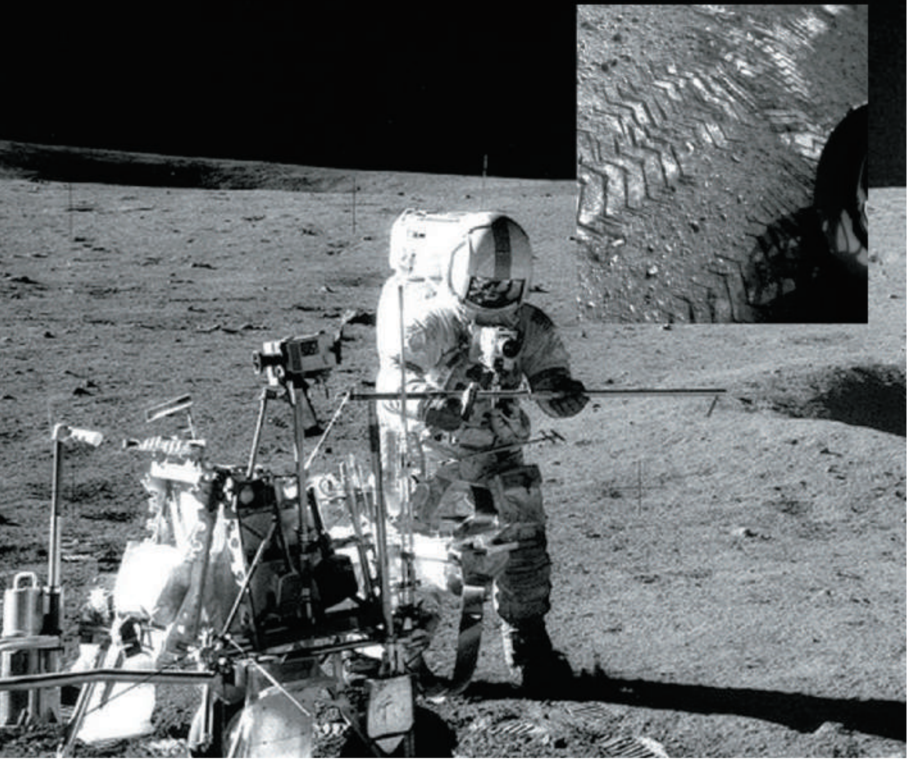
Liu, T., and C. Khosla. 2010. "A balancing act for taxol precursor pathways in e. Coli," *Science*, **330**:44–45.

Otto, C. C., and S. E. Haydel. 2013. "Exchangeable ions are responsible for the *in vitro* antibacterial properties of natural clay mixtures," *PLoS ONE*, **8**:e64068.

Rook, G. A. 2013. "Regulation of the immune system by biodiversity from the natural environment: An ecosystem service essential to health," *Proc Natl Acad Sci*., **110**:18360–18367.

Stokes, T. 2006. "The earth-eaters," *Nature*, 444:543–544.

Young, S. L., P. W. Sherman, J. B. Lucks, and G. H. Pelto. 2011. "Why on earth?: Evaluating hypotheses about the physiological functions of human geophagy," *Q Rev Bio*., **86**:97–120.



Leaving tracks in the soils of other worlds: Apollo 14 astronaut sampling lunar soil with inset showing tracks of Curiosity Rover in Mars soil. (NASA)

2
Formation of Soils from Parent Materials

It is a poem of existence . . . not a lyric but
a slow epic whose beat has been set
by eons of the world's experience. . . .
—*James Michener,* Centennial

The first astronauts to explore the moon labored in their clumsy pressurized suits to collect samples of rocks and dust from the lunar surface. These they carried back to Earth for analysis. It turned out that moon rocks are similar in composition to those found deep in the Earth—so similar that scientists concluded that the moon itself began when a stupendous collision between a Mars-sized object named Theia and the young Earth spewed molten material into orbit around the planet.[1] The force of gravity eventually pulled this material together to form the moon. On the moon, this rock remained unchanged or crumbled into dust with the impact of meteors. On Earth, the rock at the surface, eventually coming in contact with water, air, and living things, was transformed into something new, into many different kinds of living soils. This chapter reveals the story of how rock and dust become "the ecstatic skin of the Earth."[2]

We will study the processes of soil formation that transform the lifeless regolith into the variegated layers of the soil profile. We will also learn about the environmental factors that influence these processes to produce soils in Belgium so different from those in Brazil, soils on limestone so different from those on sandstone, and soils in the valley bottoms so different from those on the hills.

Every landscape is comprised of a suite of different soils, each influencing ecological processes in its own way. Whether we intend to modify, exploit, preserve, or simply understand the landscape, our success will depend on our knowing how soil properties relate to the environment on each site and to the landscape as a whole.

2.1 WEATHERING OF ROCKS AND MINERALS

Weathering breaks up rocks and minerals, modifies or destroys their physical and chemical characteristics, and carries away the finer fragments and soluble products. Nothing escapes it. However, weathering also synthesizes new minerals that influence important properties

[1]Computer simulations suggest that formation of the moon from such a collision would have resulted in the moon rock made of about 80% Theia material and 20% Earth material. Isotopic analysis of basalt rock samples some 40 years after their collection on the moon by the Apollo astronauts supports this scenario (Herwartz et al., 2014).

[2]The apt description of soil as "ecstatic skin of the Earth" is from a delightfully readable account of soils by Logan (1995). However, Earth may not be the only planet with a skin of soil. Intriguing data from Mars Rover landers and the OMEGA orbiter suggest erosion and formation of secondary minerals like gypsum from the movement and evaporation of surface water but almost no weathering and no clays. Although scientists have concluded that the Martian surface has been dry and cold since brief flooding 600 million years ago, some intriguing observation suggests still active warm season flows (Ojha, et al., 2015 and McEwen et al., 2011).

Figure 2.1 *Two stone markers, photographed on the same day in the same cemetery, illustrate the effect of rock type on weathering rates. The date and initials carved in the slate marker in 1798 are still sharp and clear, while the date and figure of a lamb carved in the marble marker in 1875 have weathered almost beyond recognition. The slate rock consists largely of resistant silicate clay minerals, whereas the marble consists mainly of calcite, which is much more easily attacked by acids in rainwater.* (Photos courtesy of Ray R. Weil)

in soils. The nature of the rocks and minerals being weathered determines the rates and results of the breakdown and synthesis (Figure 2.1).

Characteristics of Rocks and Minerals

Geologists classify Earth's rocks as igneous, sedimentary, and metamorphic. Igneous rocks are those formed from molten magma and include such common rocks as granite and diorite (Figure 2.2).

Igneous rock is composed of such primary minerals[3] as light-colored quartz, muscovite, and feldspars and dark-colored biotite, augite, and hornblende. The mineral grains in igneous rocks interlock and are randomly dispersed, giving a salt-and-pepper appearance if they are coarse enough to see with the unaided eye (Figure 2.3). In general, dark-colored minerals contain iron and magnesium and are more easily weathered. Therefore, dark-colored igneous rocks such as gabbro and basalt are more easily broken down than are granite, syenite, and other lighter-colored igneous rocks.

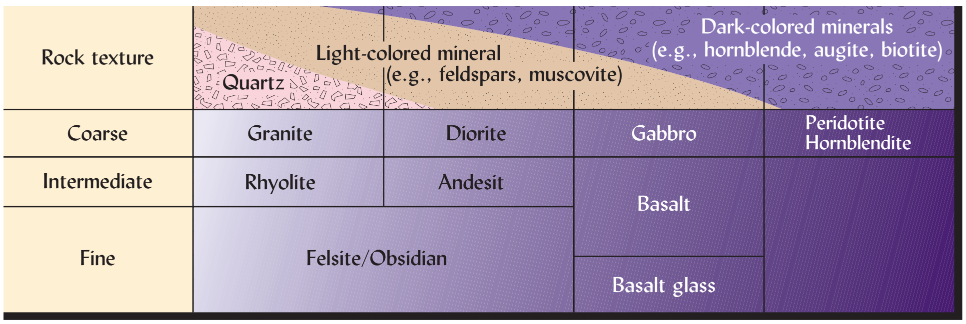


Figure 2.2 *Classification of some igneous rocks in relation to mineralogical composition and the size of mineral grains in the rock (rock texture). Worldwide, light-colored minerals and quartz are generally more prominent than the dark-colored minerals.*

[3]*Primary minerals* have not been altered chemically since they formed as molten lava solidified. *Secondary minerals* are recrystallized products of the chemical breakdown and/or alteration of primary minerals.

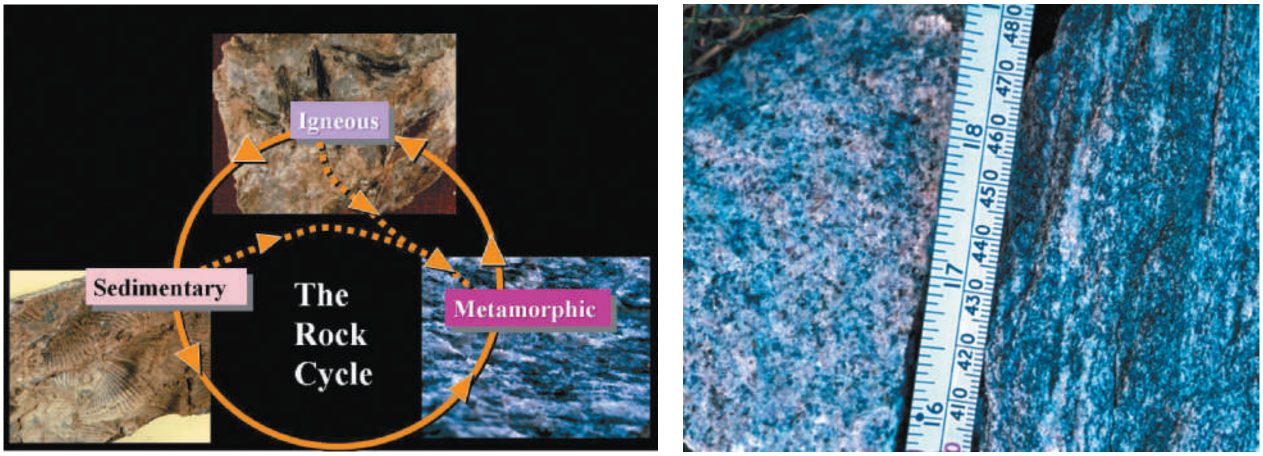


Figure 2.3 (Left) *The three rock types are interrelated by processes that comprise the rock cycle.* (Right) *Primary minerals are randomly interlocked in igneous rocks, as in the syenite to the left of the scale. High heat and pressure have deformed and reoriented the crystals and caused lighter minerals to separate from heavier ones, forming the light- and dark-colored bands typical of gneiss, a metamorphic rock on the right of the scale. In this case, the primary mineral content of both rocks is similar, the light-colored minerals being mainly feldspars and the darker ones hornblende. Scale in inches and centimeters.* (Photo courtesy of Ray R. Weil)

Sedimentary rocks form when weathering products released from other, older rocks collect under water as sediment and eventually reconsolidate into new rock. For example, quartz sand weathered from granite and deposited near the shore of a prehistoric sea may become cemented by calcium or iron in the water to become a solid mass called sandstone. Similarly, clays may be compacted into shale. Other important sedimentary rocks are listed in Table 2.1, along with their dominant minerals. The resistance of a given sedimentary rock to weathering is determined by its particular dominant minerals and by the cementing agent. Because most of what is presently dry land was at some time in the past covered by water, sedimentary rocks are the most common type of rock encountered, covering about 75% of the Earth's land surface.

Metamorphic rocks are formed from other rocks by a process of change termed "metamorphism." As Earth's continental plates shift, and sometimes collide, forces are generated that can uplift great mountain ranges or cause huge layers of rock to be pushed deep into the crust. These movements subject igneous and sedimentary rock masses to tremendous heat and pressure. These forces may slowly compress and partially remelt and distort the rocks, as well

Table 2.1
Some of the More Important Sedimentary and Metamorphic Rocks and the Minerals Commonly Dominant in Them

	Type of Rock	
Dominant Mineral	**Sedimentary**	**Metamorphic**
Calcite ($CaCO_3$)	Limestone	Marble
Dolomite ($CaCO_3 \cdot MgCO_3$)	Dolomite	Marble
Quartz (SiO_2)	Sandstone	Quartzite
Clays	Shale	Slate
Variable, silicates	Conglomerate[a]	Gneiss[b]
Variable, silicates		Schist[b]

[a]Small stones of various mineralogical makeup are cemented into conglomerate.
[b]The minerals present are determined by the original rock, which has been changed by metamorphism. Primary minerals present in the igneous rocks commonly dominate these rocks, although some secondary minerals are also present.

as break the bonds holding the original minerals together. Recrystallization during metamorphism may produce new (usually larger) crystals of the same minerals, or elements from the original minerals may recombine to form new minerals. Igneous rocks like granite may be modified to form gneiss, a metamorphic rock in which light and dark minerals have been reoriented into bands (Figure 2.3, *right*). Sedimentary rocks, such as limestone and shale, may be metamorphosed to marble and slate, respectively (Table 2.1). Slate may be further metamorphosed into phyllite or schist, which typically features mica crystallized during metamorphism.

Metamorphic rocks are usually harder and more strongly crystalline than the sedimentary rocks from which they formed. The particular minerals that dominate a given metamorphic rock influence its resistance to chemical weathering (see Table 2.2 and Figure 2.1).

Weathering: A General Case

Weathering is a biochemical process that involves both destruction and synthesis. Moving from left to right in the weathering diagram (Figure 2.4), the original rocks and minerals are destroyed by both *physical disintegration* and *chemical decomposition*. Without appreciably affecting their composition, physical disintegration breaks down rock into smaller rocks and eventually into sand and silt particles that are commonly made up of individual minerals. Simultaneously, the minerals decompose chemically, releasing soluble materials and synthesizing new minerals, some of which are resistant end products. New minerals form either by minor chemical alterations or by complete chemical breakdown of the original mineral and resynthesis of new minerals. During the chemical changes, particle size continues to decrease, and constituents continue to dissolve in the aqueous weathering solution. The dissolved substances may recombine into new (secondary) minerals, may leave the profile in drainage water, or may be taken up by plant roots.

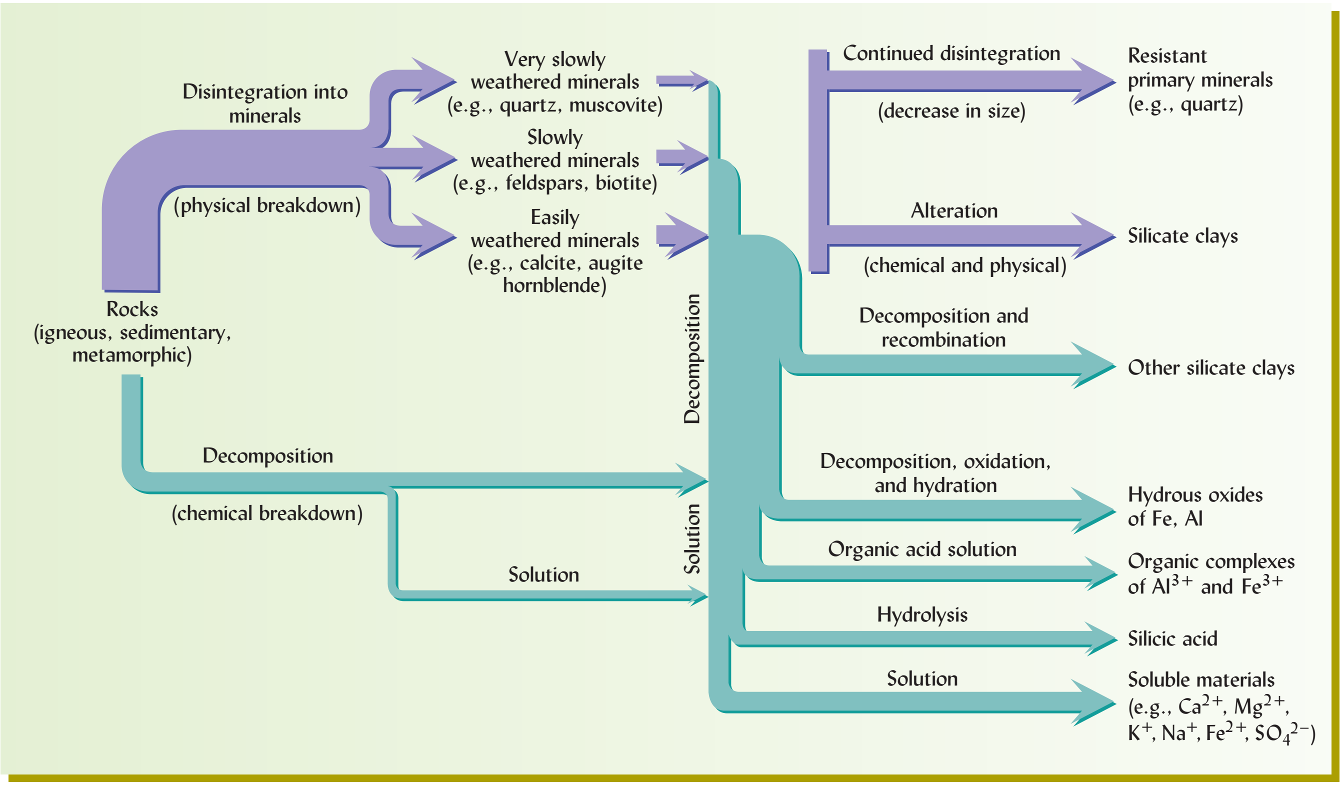


Figure 2.4 *Pathways of weathering that occur under moderately acid conditions common in humid temperate regions. The disintegration of rocks into small individual mineral grains is a physical process, whereas decomposition, recombination, and solution are chemical processes. Alteration of minerals involves both physical and chemical processes. Note that resistant primary minerals, newly synthesized secondary minerals, and soluble materials are products of weathering. In arid regions the physical processes predominate, but in humid tropical areas decomposition and recombination are most prominent.*