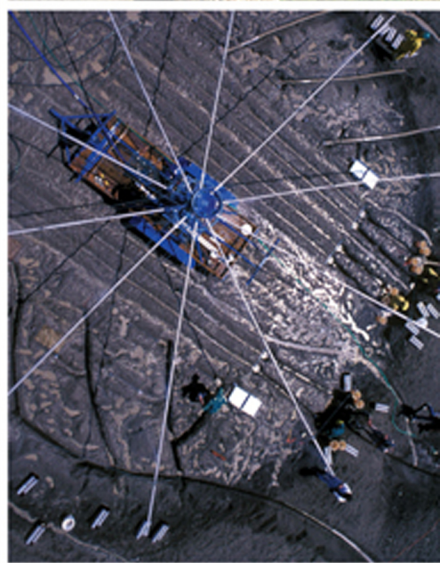


Soil Science & MANAGEMENT

SIXTH
EDITION



Edward J. Plaster

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Soil Science & MANAGEMENT

Edward J. Plaster



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Soil Science and Management, 6th Ed.
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Conceptual Approach

This sixth edition of *Soil Science and Management* continues the primary objectives of earlier editions, with the following four main purposes: (1) to acquaint the reader with the soil and water resources of the United States to enable a full appreciation of the importance of these resources; (2) to present soil science theory tied to the practice of those who use soil, mainly for growing plants; (3) to stress the sustainable management of soil and water resources by devoting detail to such subjects as soil and water conservation, conservation tillage, nutrient management, Best Management Practices, and sustainable agriculture; and (4) to relate soils to natural ecosystems.

New to the Sixth Edition

The major change to the sixth edition is an enhanced focus on horticultural soil use, particularly landscape horticulture. This change results from reviewer comments. Recognizing that many of the readers of this text do attend horticulture and landscaping programs, and that the majority of Americans live in cities and experience urban horticulture, I decided to follow the reviewer's request. Examples include coverage of landscape irrigation and drainage practices, expansion of greenhouse fertilization practices, and many others. Several mentions have also been made to LEED certification, a system for certifying "green" building construction that influences the landscape trade. It is hoped that the alterations will clarify the applicability of soil science to horticulture and engage student interest.

Since I did not wish this sixth edition to achieve doorstop weight, some coverage of agronomic practices has been condensed to make room for the new material. I feel this was achieved by deleting unnecessary details rather than weakening coverage of important ones.

Other, smaller changes are scattered liberally throughout the text. This includes updating various bits of data, expanding coverage of soil biology and geology, and providing more information on soils in the natural world. Also, since the effects of climate change have become even more pronounced, a bit more is added to that topic.

A more detailed chapter-by-chapter summary of changes follows:

Chapter 1: The section on soil uses was reworked to put greater emphasis on horticulture and landscape soil use, including an introduction to LEED certification, a third-party certification program for energy- and resource-efficient construction relevant to landscapers and landscape architects. It is also referred to elsewhere in the text. The section also introduces urban agriculture as a soil use, a topic of growing interest for many.

Chapter 1 includes a lot of data on land use and other details; most of these have been updated. Other smaller alterations appear throughout the chapter, including a bit more about Best Management Practices (BMPs) and soil's relationship to climate. An image of a rain garden was added to illustrate a BMP and an image of a staked palm to illustrate the concept of anchorage; to make room, the figure of the earth's cross section was dropped. There were minor changes in the review questions and enrichment activities.

Chapter 2: Chapter 2 now features an expanded discussion of rocks and minerals and their weathering, including an illustrative sidebar about weathering of Mount Rushmore. The accompanying drawing demonstrating the rock types was replaced by photos of actual rocks. Also new is a drawing of slope effects on soil. There are also several new review questions.

Chapter 3: There are no major changes. A sidebar was added about Histosols and climate, and a paragraph warning about some problems with published soil surveys. Some data on lands of the United States are updated, and some review and enrichment activities have been modified.

Chapter 4: Chapter 4 now exhibits more examples of soil physical properties related to horticultural soil use, including a sidebar about protecting soil from compaction around trees and a new photograph of what the soil in a yard looks like during building construction—such an indignity for soil to suffer. The section on soil temperature has been expanded because it is so important in horticulture. For example, frost heaving of plants and preventing it has been added. Also included in this section is the effect of fire on soil temperatures in natural ecosystems with an accompanying new figure; I felt it was timely given the great increase in wildfire incidence climate change is imposing on nature.

Numerous other smaller additions appear in this edition. The chapter calls out important simple practices for managing physical conditions of the soil, referring to them as axioms or cardinal rules, like “avoid bare soil.” The intent is to focus student attention on certain simple, almost universal sustainable practices. There are several new review questions, including a couple applying soil science to the landscape industry.

Chapter 5: I reworked the coverage of the soil food web, expanding it and aligning it more with classical ecological knowledge of trophic levels. A well-known United States Department of Agriculture (USDA) graphic of the soil food web has been added to illustrate the principles, and the student is invited to refer back to it as a context for the rest of the chapter.

This edition puts more emphasis on the rhizosphere, even including material on rhizosphere effects on natural plant communities. That discussion continues with the effects on soil biology from the invasion of natural ecosystems by exotic plants like buckthorn. Numerous other smaller changes are also scattered throughout the chapter, like the introduction of intercropping as a practice to increase biological diversity in a garden or field. A couple of new enrichment activities are also added, as well a couple of new figures.

Chapter 6: There are no major changes in this chapter. A sidebar was added of some interest to those who work with plants in containers concerning the water-holding capacity of their growing media. I have expanded the concept of allelopathy, adding examples from landscaping and nature. The value of permanent vegetative cover for improving soil organic matter content is stressed a bit more, as well as its use in permaculture.

There are a couple of new images and little additions scattered throughout the chapter, especially of matters related to horticulture. One reviewer asked for a photo of an organic soil profile to augment the drawing I have, and I was lucky to find a photo of peat harvesting in Ireland that shows a profile.

Chapter 7: The main change to this chapter is the addition of material on elevation contours on the land and how they affect overland water flow. I added this partly because it is very important information for a diligent landscape designer, but also because it helps understand the soil conservation practices presented in Chapter 18. There are also several new review questions.

Chapter 8: In the past, this chapter has been pretty focused on water conservation in agricultural settings. In this edition, I have added some new basic material on water conservation in urban settings. To make room, the coverage of conservation in agricultural areas is slightly less detailed.

There is some updating of data used in the chapter and a couple of new images as well.

Chapter 9: In this edition, Chapter 9 expands coverage of drainage and irrigation in landscape settings. The new material certainly cannot substitute for classes dedicated to those subjects, and anyone wanting to design and install landscape irrigation needs to take a class on the subject. The same for stormwater management. This new material should help prepare for such classes.

To make room for this new material, I condensed the material on agricultural irrigation, which probably has been more detailed than needed in a basic text. Other bits were also edited out to avoid chapter size growing larger. This also meant losing a few figures and adding a few new ones.

I also expanded the discussion on controlled drainage, with a new drawing.

Chapter 10: This edition of Chapter 10 has relatively few changes. A photomicrograph of kaolinite clay particles has been added to assist students in visualizing clay structure.

Chapter 11: The biggest alteration is the treatment of soil acidification. This topic has been expanded to accommodate those who need to acidify soils—often landscapers and gardeners who want to grow acid-loving plants. Soil acidification is a less well-developed practice than liming.

As in many chapters of this edition, there are additional examples of the chapter topic applied to horticulture and natural ecosystems; for example, effects of acid rain on some forests, seaside salt issues, or natural plant communities that grow on salted soil. To make room, I slightly condensed material on salted and sodic soils. I hope this does not inconvenience some readers too much.

There are several new review questions, all using horticultural examples.

Chapter 12: Numerous smaller additions have been made to this chapter. The subject of nitrogen leakage into the environment has been introduced in greater detail, and will be developed more in later chapters. This topic also introduces the dramatic nature of the discovery of the Haber–Bosch process. More detail is added about phosphorus, and iron and manganese toxicities are discussed in more depth—these are common problems in some horticulture applications. Many of the changes relate to horticulture.

Chapter 13: In this edition, only a few minor changes were made to this chapter. I added some references to practices in horticulture, and stressed a bit more the importance of soil testing to avoid applying fertilizers in excess of plant needs.

Chapter 14: I expanded the material on slow-release fertilizers and the Haber-Bosch process. There are new comments about materials suitable or not suitable for organic growing. As in most chapters, there are more horticultural references. To keep the text from growing ever larger, I deleted or condensed some material, including that on blending calculations and pop-up fertilizers. There is a new image of a greenhouse injector and fewer images of field application equipment. There are also a few changed review questions.

Chapter 15: The material on manure has been modified with some information added and some deleted. The benefits, and potential problems, of these amendments have been stressed more. I condensed the material on manure handling systems while emphasizing manure's potential for phosphorus loading into the environment. Composting and anaerobic digestion are mentioned as ways to handle manure. I condensed the treatment of biosolids, mainly to save space. A new brief mention of small-scale composting appears. This edition also expands on the topic of human alteration of the nitrogen cycle and its effect on the environment and human health.

Chapter 16: In keeping with my desire to keep this text from developing gigantism, I condensed this chapter. Some detail and a couple of figures have been deleted. I added a section on the concept of intercropping as a cropping system.

Chapter 17: The sections of this chapter on fruit, vegetable, and nursery production are largely unchanged. The sections on greenhouse production and landscaping have been altered with changes scattered throughout. A major addition is a sidebar on the use of fertilizer injectors, including fertilizer calculations that are different from those standard calculations in Chapter 14. Minor changes include such matters as drawbacks of horticultural peat, water-quality issues, the use of low-ammonia and low-phosphorus feeds in container production, and others.

Chapter 18: This new edition updates some erosion data. I altered the text mainly in the section on water erosion control practices, with additional material throughout. Here I also refer back to the new material in Chapter 6 on the direction of water flow over land. There are also new references to soil conservation in landscape settings, including observing that landscaping *is* a soil conservation practice. The use of polyacrylamide polymers as a soil protectant is also mentioned for the first time. There are several new review questions.

Chapter 19: Some data are updated. There is additional new material on managing urban soils, like some detail about practices for LEED certification. Two new sidebars compare and contrast two ways of installing pavers: the traditional compacted base method and the newer permeable paving method. These provide examples of both purposeful compaction and a low-impact practice. Both also illustrate what is really an engineering use of soil.

Chapter 20: To make room for other additions in the text, I condensed this chapter. It also updates content for a couple of changes in the 2008 farm bill. Unfortunately, the 2012 farm bill was sitting in Congress at the time this edition was being prepared, so the content should be augmented by the instructor when the bill is passed.

In the Enrichment Activities section at the end of the chapters, some old or defunct Web sites have been deleted or updated, and I have added a few sites of interest

that I encountered while preparing this edition. I, along with the publisher, can affirm that the Web site URLs referenced were accurate at the time of printing. However, due to the fluid nature of the Internet, we cannot guarantee their accuracy for the life of the edition. Each activity attempts to provide the user with enough information to locate the Web site even if the link becomes out of date.

Ancillary Support Materials

The following supplements provide instructors with comprehensive resources for teaching the materials found in the textbook.

Lab Manual to accompany Soil Science and Management, Sixth Edition

By Philip G. Gibson

ISBN-13: 978-0-8400-2434-3

The Lab Manual provides activities related to the text material in each chapter. Each chapter contains a purpose, an overview, activities along with a list of equipment and materials, and follow-up questions to challenge the students. Students can complete all or selected portions of each chapter's activities. In addition, many of the activities can be modified to allow students to complete them off-campus or at home. In fact, the lab activities can be easily adapted to an Internet-based soils course.

New to this edition, content has been updated to correlate with the updates made to the core textbook. In particular, Chapter 1 incorporates updates to two activities. The third activity now relates to determining the pH of vinegar using litmus paper, and the last activity provides an updated activity related to the structural support of soil. Chapter 5 now includes a new Internet-based activity and corresponding Challenge Question related to conducting a survey of soil organism genetics. Chapters 7 and 19 contain new information related to water movement and the Soil Erosion and Control Act and LEED certification, respectively.

Instructor's Resource CD-ROM to accompany Soil Science and Management, Sixth Edition

ISBN-13: 978-08400-2436-7

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- The **Lab Manual Instructor's Guide** offers instructor guidance for each lab activity found in the Lab Manual along with answers to the Challenge Questions.

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I continue to be indebted to the U.S. Department of Agriculture for the many photographs that appear in this text and the volumes of information it makes available. The Minnesota Geological Survey, which has been of assistance before, provided a fine image of kaolin clay crystals, and the Minnesota Landscape Arboretum supplied a photo of some of its display flower beds planted to a cover crop in the fall. I appreciate the input of reviewers in providing ideas for this new edition.

I want to especially thank my wife, Sue, and family. Since the last edition, a new granddaughter, Mya, joined Elena and Carrie as the younger members of the family, and all three give me great joy. I apologize to them for the time that preparing this edition has taken from my time spent with them.

Reviewers

I extend my appreciation to the reviewers who took the time to provide valuable feedback that informed the creation of this new edition.

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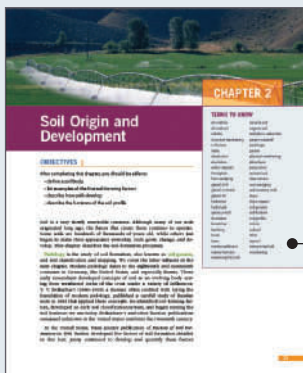
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Objectives

Learning objectives at the beginning of each chapter introduce you to the key concepts you should understand upon completion of the chapter.

Terms to Know

Each chapter begins with a list of important key terms to know. Study this list as you prepare for tests and quizzes. Key terms are emphasized in color throughout the text so you can easily identify where they are discussed in the chapter. A definition accompanies the key term in the text and each term also has a corresponding glossary definition.



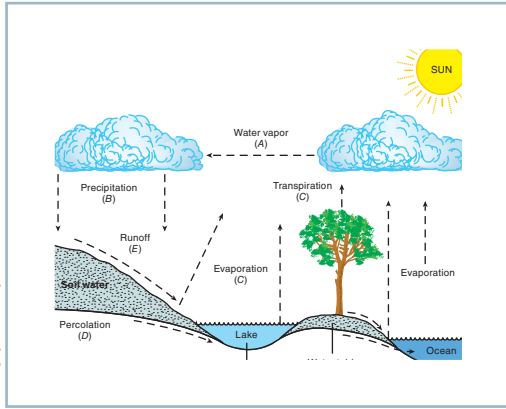
Informational Sidebars

Throughout the textbook, additional information about topics discussed in the chapter is highlighted in a sidebar feature that discusses a current event, pertinent regulation or legislation, or other relevant information related to the topic.





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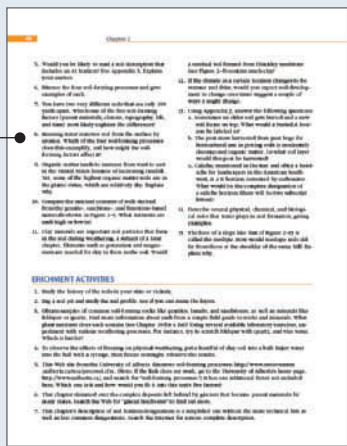
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Photographs and Illustrations

Full-color photographs and illustrations are used throughout the textbook to help you visualize important aspects of soil science and management.

End-of-Chapter Recap

Each chapter concludes with a summary that recaps important concepts discussed in the chapter. Review questions quiz your knowledge and recall of the chapter's concepts, while Enrichment Activities use the Internet to provide you with additional resources for information about concepts discussed in the chapter, including websites with simple demonstrations, research studies, and other suggestions as well.





CHAPTER 1

The Importance of Soil

OBJECTIVES

After completing this chapter, you should be able to:

- summarize ecological functions of soil and its role in recycling resources needed for plant growth
- describe four ways plants use soil
- explain how soil is a three-phase system
- list and explain uses of soil
- discuss the concept of soil quality
- describe briefly the role of soil in climate change

Life and human civilization depend on the planet's limited soil and water resources. We have ample historical proof. Most early civilizations in the Old World grew and thrived on the rich soil and waters of major river floodplains. Early Chinese culture, for instance, began to develop 6,000 to 7,000 years ago on floodplains of the Yellow River, where periodic flooding deposited fresh soil for agriculture and canals could carry river water to fields for irrigation. Similarly, farming began to flourish some 10,000 years ago in the Mideast along major rivers.

The famous Greek historian Herodotus left us his notes about the dependence of Egypt on soil supplied by flooding of the Nile. In 340 B.C.E., in *The History of Herodotus*, he observed that black, crumbly, silty river deposits were easy to work and productive—these soils could produce plentiful food with less toil. These soils, he noted, were the foundation for Egyptian civilization.

North America too depends on its soil and water, and our history was influenced by its soils. Part of its success stands on rich soil and water resources; those of the United States are described later in this chapter

TERMS TO KNOW

aeration pore	nutrient
anchorage	photosynthesis
Best Management Practice (BMP)	pore space
carbon sequestration	respiration
carbon sink	shrink-swell potential
cropland	soil aeration
desertification	soil air
hardpan	soil degradation
hydroponic crop	soil matrix
load-bearing capacity	soil quality
macropore	soil solution
micropore	waterlogged soil

Figure 1-1

A Dust Bowl “roller” moves across a Colorado landscape, carrying off soil and damaging everything in its path. Events such as this have reappeared with recent prolonged drought in the Great Plains. Photos of such a roller over Phoenix appeared in the news as this edition was being prepared.



Photo courtesy of USDA Natural Resources Conservation Service

and throughout the text. But we have often not been wise in their use. The Dust Bowl of the 1930s, caused by drought, soil misuse, and widespread wind erosion, drove farmers out of several middle plains states. At its peak, severe wind erosion damaged some 150,000 square miles of prairie farmland (Figure 1-1). By 1940, 2.5 million people had moved out of the Great Plains, forced out by drought, unsustainable land-use practices, and depression. Photographs from that era create striking and poignant images of people driven off their land by the destruction of the Dust Bowl and scattered to new lives elsewhere (Figure 1-2).

Soil and water resource problems also cross national borders, sometimes in ways hard to imagine. For instance, North and South America and Europe receive dust blown from desert lands of Africa. As soils of Africa degrade, that movement of dust has been increasing. More obviously, shortages of soil and water resources cause conflicts and migration of refugees.

In the future, soil will become even more crucial. As this edition was being prepared, the earth's population reached 7 billion; some estimates expect it to reach 9 billion by 2050, well within the lifetime of most students reading this text. Yet only about 7 percent of the earth's surface is suitable for agriculture, and that figure is not going to increase. Of that land, some is being lost to degradation and urbanization. A late-2011 report by the United Nations Food and Agriculture Organization (*The State of the World's Land and Water Resources for Food and Agriculture 2011*) found a quarter of the world's land to be highly degraded. It further noted that the world's growers will need to provide 70 percent more food by 2050. Unfortunately, soil cannot easily be replaced: Soil is a nonrenewable resource within the time frame of a human generation.

Many experts have noted that part of the rhythm of human history is the rise and fall of cultures founded on the use, abuse, and final exhaustion of soil and water

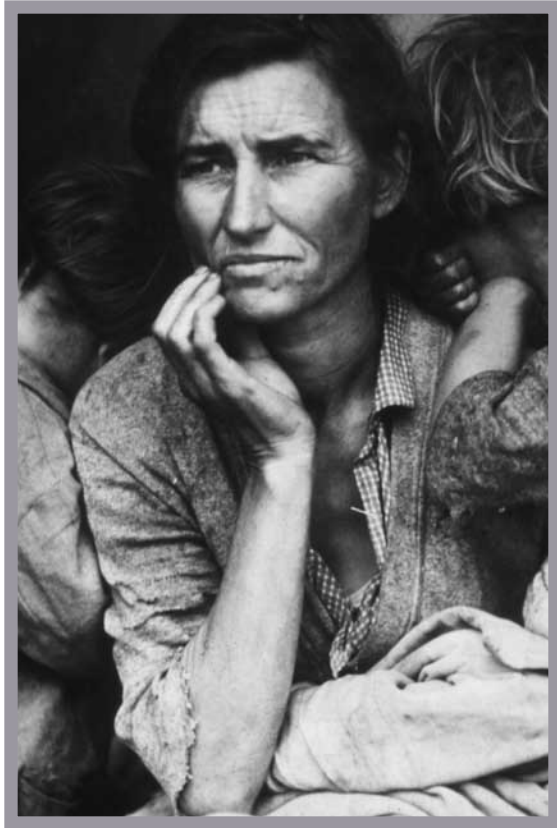


Photo by Dorothea Lange, USDA Natural Resources Conservation Service

Figure 1-2

A famous Dorothea Lange photograph of a migrant worker in California displaced by the Dust Bowl.

resources. Some once-productive land of the ancient Fertile Crescent, in modern-day Iraq, now lies barren because of salts built up from centuries of irrigation from the Tigris and Euphrates rivers. This is not simply a problem of the past, but of today.

Human society—indeed, most life—is possible only because earth’s crust is dusted with a bit of soil where we can grow food. Most of the world’s soils capable of being farmed without causing great environmental damage are already being farmed, thus the importance of making productive and sustainable use of those soils. This book is dedicated to describing those soil and water resources and how we can use them wisely. We begin by looking at soil’s ecological functions in supporting life on the planet, its role as a medium for plant growth, and its use by humans.

SOIL IS A LIFE-SUPPORTING LAYER OF MATERIAL

Although we take soil for granted, it is a very thin and often fragile layer of life-supporting material. We all stand on the rocky solid surface of the earth, the continental crust, which is generally about 50 miles thick. We breathe the air of the atmosphere, which is about 22 miles deep (though there is no measurable edge). Soil forms a very thin interface between the two.

The atmosphere, crust, and soil interact to provide plants and animals with the resources they need. Living things need proper temperature, oxygen, water, carbon (the basic element of all living bodies), and other nutrients. These factors are exchanged in the soil, as shown in Figure 1–3, usually in cycles that allow elements to be recycled and stored rather than lost. Although later chapters will discuss the cycles in greater detail, this chapter previews them briefly.

Temperature

Plant roots grow best in certain soil temperature ranges. For instance, most plant roots in temperate climates grow at soil temperatures above 40°F to 50°F. The cool-season grasses grown in northern states cease root growth at soil temperatures above 85°F. Seed germination also depends on soil temperature; wheat seed, for example, germinates between 40°F and 50°F, while sorghum needs temperatures above 80°F. Soil temperature, and to some degree the air above the soil, is controlled by a heat-exchange mechanism.

Pedestrians standing on a tar road on a hot summer day sense how heat is exchanged as the road both gains and loses heat. Feet in contact with pavement get

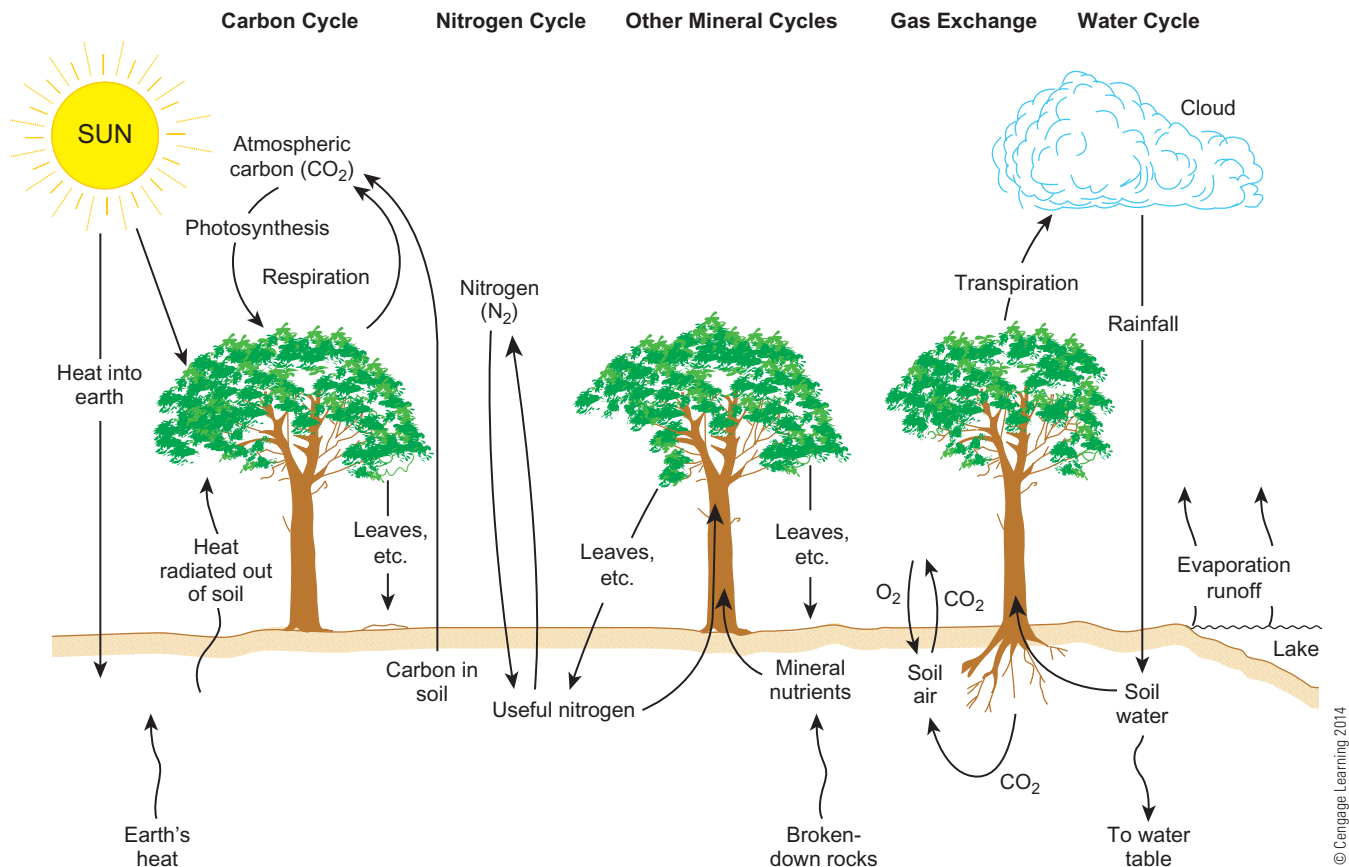


Figure 1–3

Cycling and exchange between atmosphere, crust, and soil. The soil temporarily stores resources needed for plant growth.

hot because the road is absorbing energy from the sun. Looking down the road, one sees heat waves rising from the tar, an effect of the road losing excess heat to the air. Energy is also radiating away as light in a wavelength that humans cannot see. In the same way, soil maintains temperatures for growing plants. On a larger scale, this heat exchange influences air temperature, weather, and even global climate.

Gases

Plant roots and other soil organisms need oxygen and give off carbon dioxide as they respire. Some important soil bacteria need nitrogen gas as well. Figure 1–3 shows that these gases pass into and out of the soil to maintain proper amounts of each. In this process of air exchange, soil also acts to filter and purify the earth's atmosphere.

Water

Water seldom stays in one place long, always being on its way to the next stage of its cycle. Water evaporates from land, lakes, and oceans and forms clouds in the atmosphere. Rain falls from the clouds, moistens the soil, and fills streams and lakes. Most of the water finally reaches the oceans, where evaporation begins the cycle again. Some water seeps deep into the ground where it is held as groundwater. When moisture falls on the soil, however, some water is temporarily stored for plant use. In the process, soil filters water as it moves through the soil, purifying it.

Carbon

Plant leaves collect sunlight to use the sun's energy in the process known as **photosynthesis**, which involves converting atmospheric carbon (carbon dioxide) to biological carbon (simple sugars). In the process, light energy is converted to chemical energy usable by plants and creatures that eat plants. Some of the carbon is recycled directly back to the atmosphere by plant and animal **respiration**, while other carbon is recycled by organic matter decay in the soil. In this process, some carbon is retained in the soil as organic matter. Soil acts as a vast carbon reserve keeping carbon dioxide out of the atmosphere, where it would contribute to the greenhouse effect.

Nutrients

Plant **nutrients** (chemicals a plant needs to grow) also cycle through the soil. Two kinds of nutrient cycles are shown in Figure 1–3: the nitrogen cycle and other mineral cycles.

Nitrogen comes entirely from the atmosphere, where it occurs as a gas, a form that plants cannot use. Soil organisms convert gaseous nitrogen to forms that plants can use. Some nitrogen recycles as once-living material decays in the soil, while water carries some nitrogen deeper into the ground. Some nitrogen returns to the air when other microbes change it back to its original form.

Other nutrients are released from rocks in the earth's crust when the rocks are broken down by weather, plants, and other factors. These nutrients are continuously reused by plants until some return deep into the ground by leaching, get washed into the ocean, or are removed by cropping.

SOIL IS A MEDIUM FOR PLANT GROWTH

In the broad view, soil has important ecological functions in recycling resources needed for all life. In the narrow view, an individual plant depends on soil for four needs: **anchorage**, water, oxygen, and nutrients. Let us look at these four needs.

Anchorage

In deep soil, where roots grow freely, plants are firmly supported, or anchored, so they can grow to reach for sunlight. When people grow plants in ways that deprive plants of soil support, artificial support is often required. Growers of **hydroponic crops** (roots growing not in soil but in fertilizer solutions) support plants with a wire framework. Landscapers may stake or “guy” a newly planted tree until the tree is firmly rooted (Figure 1–4), though staking weakens or even damages the trunk and is no longer recommended for regular use except in special cases like palms. Poorly anchored trees can even cause serious safety or economic issues, as they may topple in windstorms and damage cars or buildings, or even land on people.

Water

Because roots are a plant’s water-absorbing body, soil supplies the water a plant uses. For each pound of dry matter produced by growth, plants obtain between 200 and 1,000 pounds of water from the soil for photosynthesis, sap flow, and other



Image courtesy of Ed Plaster

Figure 1–4

Because of the way palm trees are transplanted, the soil cannot function well to anchor the tree, so they need to be staked, as in these trees in Florida.

uses. It is obvious that water-holding capacity of a soil is important in its agricultural and horticultural use.

Oxygen

Except for some microscopic organisms, all living creatures, including plants, need oxygen. Plants release oxygen during photosynthesis, but consume it during respiration. The parts of a plant above the ground, suspended in an atmosphere that is 21 percent oxygen (Figure 1–5), have all the oxygen they need. Underground, plant roots and soil organisms use up oxygen and give off carbon dioxide. As a result, **soil air** has less oxygen and more carbon dioxide than the atmosphere. The resulting concentration gradients between soil and atmosphere cause oxygen to diffuse into the soil and carbon dioxide to diffuse out.

In the absence of factors that limit it, this process, known as **soil aeration**, exchanges soil and atmospheric air to maintain adequate oxygen for plant roots. Aeration varies according to soil condition. Saturated, or **waterlogged soil**, which is completely soaked with water, is an example of a soil with poor aeration. The oxygen content near the surface of a well-aerated soil rarely drops below 20 percent, but may approach 0 in a saturated soil.

Nutrients

Of 17 nutrients usually considered to be needed by most plants, plants absorb 14 from soil. Carbon, oxygen, and hydrogen come from air and water; the rest are from the soil. Nitrogen comes indirectly from the atmosphere via the soil. While leaves are able to absorb some nutrients, roots are specialized for the purpose. Root hairs absorb plant nutrients dissolved in soil water (called the **soil solution**) by an active process that moves nutrients into root cells. The energy that powers this process is produced by respiration in the roots.

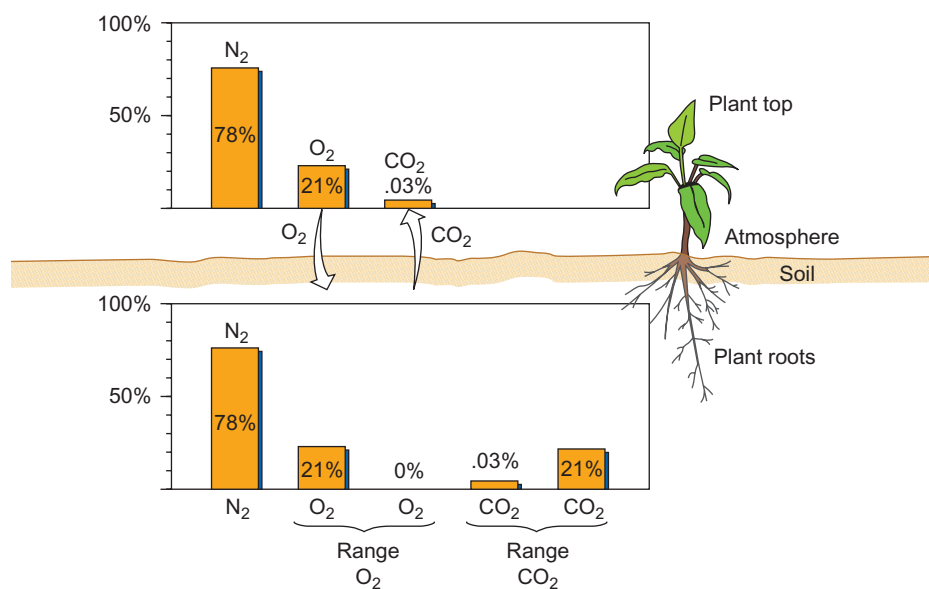


Figure 1–5

Soil air and aeration. Most of the gas in air and soil is nitrogen. Above the soil, air is about 21 percent oxygen. In the soil, respiration of living things replaces oxygen with carbon dioxide. Aeration is the process by which carbon and oxygen are exchanged.

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SOIL: A THREE-PHASE SYSTEM

How does soil fulfill the four functions described? Any grower knows that soil is made of solid particles. In most soils, solid particles largely consist of mineral matter with about 1 percent to 10 percent organic material. Between these solid particles are open spaces, or voids, which we call **pore spaces**. This arrangement of solid particles and pore spaces is called the **soil matrix**. Commonly, about half the volume of soil is solid material and half is pore space, and we consider this a good composition for plant growth.

Pore space is always filled with some combination of air and water (Figure 1–6). Chemists call solids, liquids, and gases phases of matter, so we can describe soil as a three-phase system. A combination of about half air and half water in the pores provides an excellent supply of both for roots, but the actual ratio varies dramatically over time. Right after a heavy rain, pores may be filled almost entirely with water and have almost no air. As soil dries, air replaces water in the pore spaces, and pores in a very dry soil may contain almost entirely air and very little water. These soils are too wet or too dry for good plant growth. We generally consider equal amounts of air and water as ideal for plant growth.

The amount and composition of soil air varies not only over time, but in space as well. That is, it varies greatly from spot to spot within the soil matrix. A large pore may be rich in oxygen, while a small pore a fraction of an inch away contains water and is devoid of oxygen. Those large pores, called **macropores** or **aeration pores**, are largely responsible for easy movement of air and water in the soil, and for providing space for air, while smaller **micropores** retain water for plant use.

Generally, soil is richest in oxygen near the surface, while deeper layers may be very low in oxygen because the atmosphere is farther away and pathways for diffusion are much longer. This, in turn, influences distribution of roots in soil.

Because roots require oxygen, lack of aeration poses a serious problem for plant health. Plant growth suffers greatly if air-filled porosity falls below 20 percent, or if 80 percent to 90 percent of pore space fills with water.

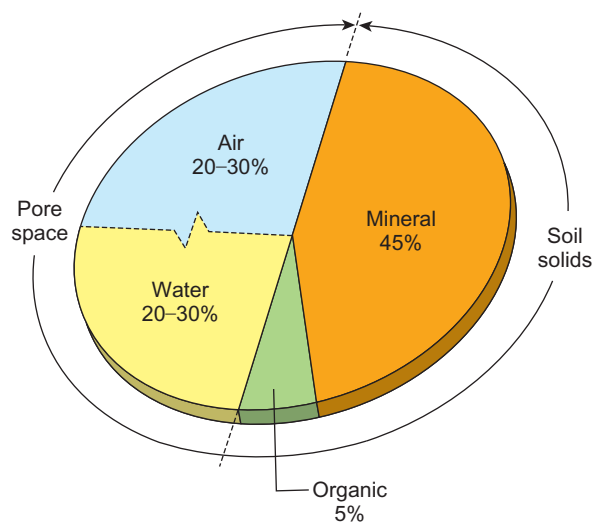


Figure 1–6

Composition of a typical soil desirable for plant growth. It contains equal proportions of solid particles and pore space, and air and water occupy equal proportions of the pore space. The proportions of air and water vary, as shown by the broken line, but ideally are within the range shown. These measurements are by volume.

Root Growth

Plants need a sufficient volume of quality soil to host roots and supply needed resources. Figure 1–7 shows two rows of urban trees. The row on the left was planted in small tree pits surrounded by pavement; the trees are stunted. The row on the right, planted at the same time, enjoys open soil where roots have room to grow; the trees are much larger and darker green.

From a root's point of view, it is pores that matter. As roots grow into the soil, they follow continuous pore spaces between solid particles, absorbing water and nutrients from the soil solution. Root tips easily penetrate pores larger than themselves. Behind the root tip, the diameter of the root increases, pushing aside or deforming the soil to make room for itself. Root tips may also enter smaller pores if the root can exert enough pressure to deform soil ahead of the tip. If pores are too small or discontinuous, or if soil particles are too difficult to push aside, root growth suffers. Such conditions can result if soil is severely compressed or compacted; in such soil, roots may only be able to follow cracks or other channels in the soil.

Water reaches roots in two ways: either water flows toward the root, or the root grows into moist soil. Roots spread to contact as much soil as possible; for trees, they typically extend up to three times the spread of the canopy (Figure 1–8). One authority estimated that a mature oak tree has about 1 million live root tips. Alfalfa roots grow to a depth of 5 or 6 feet and may go much deeper in loose soils. However, roots do not grow below the depth of aeration, unless they are specially adapted to do so, so most roots do not extend below 5 or 6 feet.

While roots try to grow widely or deeply, they grow best and the thickest where oxygen, water, or nutrients are present in optimal amounts. Roots are able to sense



Image courtesy of Ed Piaster

Figure 1–7

Street trees in St. Paul, Minnesota. The stunted trees on the left grow in small tree pits, surrounded by concrete, while the larger trees on the right grow in a turf area with plenty of soil for roots. The trees are the same age.