

THE NATURE  
AND PROPERTIES  
OF SOILS

ELEVENTH EDITION



NYLE C. BRADY  
RAY R. WEIL



# The Nature and Properties of Soils

ELEVENTH EDITION

**NYLE C. BRADY**

EMERITUS PROFESSOR OF SOIL SCIENCE  
CORNELL UNIVERSITY

**RAY R. WEIL**

PROFESSOR OF SOIL SCIENCE  
UNIVERSITY OF MARYLAND AT COLLEGE PARK



PRENTICE HALL  
UPPER SADDLE RIVER, NEW JERSEY 07458

Library of Congress Cataloging-in-Publication Data

Brady, Nyle C.

The nature and properties of soils / Nyle C. Brady. Raymond R. Weil. — 11th ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-02-313371-6

1. Soil science. 2. Soils. I. Weil, Raymond R. II. Title.

S591.B79 1996

631.4—dc20

95-41059

CIP

Production Editor: *Adele Kupchik*

Managing Editor: *Mary Carnis*

Acquisitions Editor: *Charles Stewart*

Manufacturing Buyer: *Ilene Sanford*

Director of Manufacturing & Production: *Bruce Johnson*

Editorial Assistants: *Meryl Chertoff & Mollie Pfeiffer*

Marketing Manager: *Debbie Yarnell*

Formatting/page make-up: *North Market Street Graphics*

Interior illustrations: *Mark Ammerman*

Printer/Binder: *Van Hoffman Press*

Cover Designer: *Eileen Burke*

Cover Photo: *Grant Wood's "Young Corn" courtesy of Cedar Rapids Museum of Art.*



© 1996 by Prentice-Hall, Inc.

A Simon & Schuster Company

Upper Saddle River, New Jersey 07458

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Earlier editions by T. Lyttleton Lyon and Harry O. Buckman copyright 1922, 1929, 1937, and 1943 by Macmillan Publishing Co., Inc. Earlier edition by T. Lyttleton, Harry O. Buckman, and Nyle C. Brady copyright 1952 by Macmillan Publishing Co., Inc. Earlier editions by Harry O. Buckman and Nyle C. Brady copyright © 1960 and 1969 by Macmillan Publishing Co., Inc. Copyright renewed 1950 by Bertha C. Lyon and Harry O. Buckman, 1957 and 1965 by Harry O. Buckman, 1961 by Rita S. Buckman. Earlier editions by Nyle C. Brady copyright © 1974, 1984 and 1990 by Macmillan Publishing Company.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-02-313371-6

Prentice-Hall International (UK) Limited, London

Prentice-Hall of Australia Pty. Limited, Sydney

Prentice-Hall Canada Inc., Toronto

Prentice-Hall Hispanoamericana, S.A., Mexico

Prentice-Hall of India Private Limited, New Delhi

Prentice-Hall of Japan, Inc., Tokyo

Simon & Schuster Asia Pte. Ltd., Singapore

Editora Prentice-Hall do Brasil, Ltda., Rio de Janeiro



## PREFACE

A fundamental knowledge of soil science is a prerequisite to meeting the many natural-resource challenges that will face humanity in the 21st century. This new edition of the classic book on soil science emphasizes the soil as a natural resource and highlights the many interactions between the soil and other components of the ecosystem. Throughout the text, soil properties and processes are illustrated with examples from forest, range, agricultural, wetland, and constructed ecosystems. Our priority is to explain the fundamental principles of soil science that have applications relevant to students in many fields of study. We recognize that for some students this book will be their only formal exposure to soil science, while for other students this book represents the initial step in a comprehensive soil science education.

We have therefore sought the advice of professors and students to help us make this book an exciting introduction to the fascinating world of soil science. We also intend for this book to be a “keeper,” one that will serve natural-resource and agricultural students as a reliable reference as they pursue their professional activities in the years to come. Therefore, while much is new in substance and style in this edition, we have been careful to maintain the level of rigor and thoroughness that has made previous editions so valuable.

The study of soils can be both fascinating and intellectually satisfying. The soil is an ideal system in which to observe practical applications for basic principles of biology, chemistry, and physics. In turn, these principles can be used to minimize the degradation and destruction of one of our most important natural resources.

We gratefully acknowledge the able research and editorial assistance of Karen Lowell and Joyce Torio. The book has greatly benefited from comments and suggestions contributed by many colleagues, especially those in universities around the country who responded to our questionnaire on the 10th edition. For their advice and counsel we would like to give special thanks to Hari Eswaran, Sharon Waltman, and Diane Shields (USDA/NRCS), George Ley (Tanzania Ministry of Agriculture), Bruce James, Martin Rabenhorst, Paul Shipley, and Richard Weismiller (University of Maryland).

Last, but not least, we must express our special thanks to our wives, Martha and Trish, for their constant encouragement and for their permitting us to utilize almost every free moment during the past 18 months to concentrate on the revision of this textbook.

*N. C. B. and R. R. W.*

# CONTENTS

## PREFACE xi

## I THE SOILS AROUND US I

1.1 Functions of Soils in Our Ecosystem	2
1.2 Medium for Plant Growth	3
1.3 Regulator of Water Supplies	5
1.4 Recycler of Raw Materials	6
1.5 Habitat for Soil Organisms	7
1.6 Engineering Medium	7
1.7 Soil As a Natural Body	8
1.8 The Soil Profile and Its Layers (Horizons)	10
1.9 Topsoil and Subsoil	12
1.10 Soil: The Interface of Air, Minerals, Water, and Life	13
1.11 Mineral (Inorganic) Constituents of Soils	15
1.12 Soil Organic Matter	16
1.13 Soil Water: A Dynamic Solution	17
1.14 Soil Air: A Changing Mixture of Gases	19
1.15 Interaction of Four Components to Supply Plant Nutrients	20
1.16 Nutrient Uptake by Plant Roots	23
1.17 Conclusion	24

## 2 FORMATION OF SOILS FROM PARENT MATERIALS 25

2.1 Weathering of Rocks and Minerals	26
2.2 Physical Weathering (Disintegration)	28
2.3 Chemical Processes of Weathering (Decomposition)	29
2.4 Parent Materials	32
2.5 Residual Parent Material	34
2.6 Colluvial Debris	34
2.7 Alluvial Stream Deposits	35
2.8 Marine Sediments	38
2.9 Parent Materials Transported by Ice and Melt Waters	39



2.10	Parent Materials Transported by Wind	41
2.11	Organic Deposits	43
2.12	Climate	45
2.13	Biota: Living Organisms	46
2.14	Topography	48
2.15	Time	49
2.16	Soil Formation in Action	50
2.17	The Soil Profile	52
2.18	Conclusion	55
	References	55
3	SOIL CLASSIFICATION	57
3.1	Concept of Individual Soils	57
3.2	Comprehensive Classification System: <i>Soil Taxonomy</i>	58
3.3	Categories of Soil Taxonomy	65
3.4	Nomenclature of Soil Taxonomy	67
3.5	Soil Orders	67
3.6	Entisols (Recent: Little if any Profile Development)	69
3.7	Inceptisols (Few Diagnostic Features: Inception of B Horizon)	70
3.8	Andisols	72
3.9	Mollisols (Dark Soils of Grassland: <i>Mollis</i> , Soft)	74
3.10	Alfisols (Argillic or Natric Horizon, Medium-High Bases)	78
3.11	Ultisols (Argillic Horizon, Low Bases)	79
3.12	Oxisols (Oxic Horizon, Highly Weathered)	81
3.13	Vertisols (Dark, Swelling Clays)	82
3.14	Aridisols (Dry Soils)	85
3.15	Spodosols (Acid, Sandy, Forest Soils, Low Bases)	87
3.16	Histosols (Organic Soils)	88
3.17	Key to Soil Orders	90
3.18	Soil Suborders, Great Groups, and Subgroups	91
3.19	Soil Families and Series	94
3.20	Field Configurations	95
3.21	Conclusions	96
	References	96
4	SOIL ARCHITECTURE AND PHYSICAL PROPERTIES	98
4.1	Soil Color	99
4.2	Soil Texture (Size Distribution of Soil Particles)	100
4.3	Mineralogical and Chemical Compositions of Soil Separates	105
4.4	Soil Textural Classes	106
4.5	Determination of Soil Textural Class	108
4.6	Structure of Mineral Soils	111
4.7	Particle Density of Mineral Soils	114
4.8	Bulk Density of Mineral Soils	114
4.9	Pore Space of Mineral Soils	119
4.10	Aggregation and Its Promotion in Arable Soils	124
4.11	Aggregate Stability	128
4.12	Structural Management of Soils	131
4.13	Tilth and Tillage	133
4.14	Soil Consistence and Engineering Implications	137
4.15	Conclusion	140
	References	141
5	SOIL WATER: CHARACTERISTICS AND BEHAVIOR	143
5.1	Structure and Related Properties of Water	144
5.2	Capillary Fundamentals and Soil Water	145

5.3	Soil Water Energy Concepts	149
5.4	Soil Moisture Content and Soil Water Potential	153
5.5	Measuring Soil Water Content and Water Potential	155
5.6	Types of Soil Water Movement	160
5.7	Saturated Flow through Soils	160
5.8	Unsaturated Flow in Soils	162
5.9	Water Movement in Stratified Soils	163
5.10	Water Vapor Movement in Soils	165
5.11	Retention of Soil Water in the Field	166
5.12	Conventional Soil Water Classification Schemes	168
5.13	Factors Affecting Amount of Plant-Available Soil Water	170
5.14	How Plants Are Supplied with Water: Capillarity and Root Extension	172
5.15	Conclusion	174
	References	175
6	THE SOIL AND THE HYDROLOGIC CYCLE	176
6.1	Sources of Water	176
6.2	The Hydrologic Cycle	177
6.3	Fate of Precipitation and Irrigation Water	178
6.4	The Soil–Plant–Atmosphere Continuum	181
6.5	Evapotranspiration	184
6.6	Magnitude of Evaporation Losses	186
6.7	Efficiency of Water Use	187
6.8	Control of Evapotranspiration (ET)	189
6.9	Control of Surface Evaporation (E)	191
6.10	Climatic Zone Management Practices	193
6.11	Types of Liquid Losses of Soil Water	194
6.12	Percolation and Leaching: Methods of Study	195
6.13	Percolation Losses of Water	195
6.14	Percolation and Groundwaters	197
6.15	Movement of Chemicals in the Drainage Water	199
6.16	Human Enhancement of Supplies and Outflow of Soil Water	200
6.17	Land Drainage	200
6.18	Surface Field Drains	202
6.19	Subsurface (Underground) Drains	202
6.20	Benefits of Land Drainage	206
6.21	Irrigation	208
6.22	Methods of Irrigation	209
6.23	Water-Use Efficiency	210
6.24	Irrigation Water Management	211
6.25	Conclusion	211
	References	212
7	SOIL AIR AND SOIL TEMPERATURE	213
7.1	Soil Aeration Characterized	213
7.2	Soil Aeration Problems in the Field	214
7.3	Means of Characterizing Soil Aeration	215
7.4	Factors Affecting Soil Aeration	219
7.5	Effects of Soil Aeration	221
7.6	Aeration in Relation to Soil and Plant Management	224
7.7	Areas Requiring Special Management	225
7.8	Soil Temperature	227
7.9	Absorption and Loss of Solar Energy	230
7.10	Specific Heat of Soils	232
7.11	Heat of Vaporization	232

7.12	Thermal Conductivity in Soils	234
7.13	Soil Temperature Data	235
7.14	Soil Temperature Control	236
7.15	Conclusion	239
	References	239
<b>8</b>	<b>SOIL COLLOIDS: THEIR NATURE AND PRACTICAL SIGNIFICANCE</b>	<b>241</b>
8.1	General Properties of Soil Colloids	241
8.2	Types of Soil Colloids	242
8.3	Adsorbed Cations	245
8.4	Fundamentals of Layer Silicate Clay Structure	246
8.5	Mineralogical Organization of Silicate Clays	248
8.6	Genesis of Soil Colloids	253
8.7	Geographic Distribution of Clays	256
8.8	Source of Constant Charges on Silicate Clays	257
8.9	pH-Dependent Charges	258
8.10	Cation Exchange	262
8.11	Cation Exchange Capacity	263
8.12	Exchangeable Cations in Field Soils	266
8.13	Cation Exchange and the Availability of Nutrients	267
8.14	Anion Exchange	268
8.15	Physical Properties of Colloids	269
8.16	Conclusion	270
	References	270
<b>9</b>	<b>SOIL REACTION: ACIDITY AND ALKALINITY</b>	<b>271</b>
9.1	Sources of Hydrogen and Hydroxide Ions	272
9.2	Classification of Soil Acidity	276
9.3	Colloidal Control of Soil Reaction	277
9.4	Buffering of Soils	279
9.5	Buffer Capacity of Soils	281
9.6	Changes in Soil pH	282
9.7	Soil Reaction: Correlations	288
9.8	Determination of Soil pH	291
9.9	Methods of Intensifying Soil Acidity	293
9.10	Decreasing Soil Acidity: Liming Materials	294
9.11	Reactions of Lime in the Soil	295
9.12	Lime Requirements: Quantities Needed	298
9.13	Influence of Chemical Composition and Fineness of Liming Materials	298
9.14	Practical Considerations	300
9.15	Ameliorating Acidity in Subsoils	303
9.16	Lime and Soil Fertility Management	304
9.17	Conclusion	305
	References	305
<b>10</b>	<b>ALKALINE AND SALT-AFFECTED SOILS AND THEIR MANAGEMENT</b>	<b>307</b>
10.1	Normal Alkaline Soils of Dry Areas	307
10.2	Development of Saline and Sodic Soils	309
10.3	Measuring Salinity and Alkalinity	311
10.4	Classes of Salt-Affected Soils	313
10.5	Growth of Plants on Saline and Sodic Soils	316
10.6	Tolerance of Higher Plants to Saline and Sodic Soils	316
10.7	Management of Saline and Sodic Soils	318
10.8	Reclamation of Saline Soils	320



10.9	Reclamation of Saline-Sodic and Sodic Soils	321
10.10	Management of Reclaimed Soils	325
10.11	Conclusion	325
	References	326
<b>11 ORGANISMS AND ECOLOGY OF THE SOIL</b>		<b>327</b>
11.1	Types of Organisms in the Soil	328
11.2	Organisms in Action	328
11.3	Organism Abundance, Biomass, and Metabolic Activity	332
11.4	Earthworms	334
11.5	Termites	337
11.6	Soil Microanimals	340
11.7	Roots of Higher Plants	341
11.8	Soil Algae	344
11.9	Soil Fungi	344
11.10	Soil Actinomycetes	350
11.11	Soil Bacteria	352
11.12	Conditions Affecting the Growth of Soil Bacteria	353
11.13	Competition Among Soil Organisms	353
11.14	Effects of Agricultural Practice on Soil Organisms	354
11.15	Beneficial Effects of Soil Organisms	354
11.16	Injurious Effects of Soil Organism on Higher Plants	357
11.17	Conclusion	359
	References	359
<b>12 SOIL ORGANIC MATTER</b>		<b>361</b>
12.1	The Global Carbon Cycle	361
12.2	Soils and the Greenhouse Effect	364
12.3	Carbon Cycling in Soil–Plant–Atmosphere System	365
12.4	Composition of Plant Residues	368
12.5	Decomposition of Organic Compounds	369
12.6	Decomposition in Anaerobic Soils	371
12.7	Carbon/Nitrogen Ratio of Organic Materials	372
12.8	Influence of Carbon/Nitrogen Ratio on Decomposition	372
12.9	Humus: Genesis and Nature	376
12.10	Direct Influences of Organic Matter on Plant Growth	380
12.11	Influence of Organic Matter on Soil Properties and the Environment	382
12.12	Amount of Organic Matter in Soils	383
12.13	Factors Affecting Soil Organic Matter	384
12.14	Management of Amount and Quality of Soil Organic Matter	390
12.15	Organic Soils (Histosols)	393
12.16	Organic Materials for Potting Media	394
12.17	Composts and Composting	395
12.18	Conclusion	396
	References	398
<b>13 NITROGEN AND SULFUR ECONOMY OF SOILS</b>		<b>400</b>
13.1	Influence of Nitrogen on Plant Growth and Development	401
13.2	Origin and Distribution of Nitrogen	403
13.3	The Nitrogen Cycle	403
13.4	Immobilization and Mineralization	404
13.5	Ammonium Fixation by Clay Minerals	405
13.6	Ammonia Volatilization	407
13.7	Nitrification	408

13.8	The Nitrate Leaching Problem	410
13.9	Gaseous Losses by Denitrification	413
13.10	Biological Nitrogen Fixation	418
13.11	Symbiotic Fixation with Legumes	421
13.12	Symbiotic Fixation with Nonlegumes	424
13.13	Nonsymbiotic Nitrogen Fixation	426
13.14	Addition of Nitrogen to Soil in Precipitation	427
13.15	Reactions of Nitrogen Fertilizers	428
13.16	Practical Management of Soil Nitrogen in Agriculture	429
13.17	Importance of Sulfur	431
13.18	Natural Sources of Sulfur	432
13.19	The Sulfur Cycle	435
13.20	Behavior of Sulfur Compounds in Soils	435
13.21	Sulfur Oxidation and Reduction	439
13.22	Sulfate Retention and Exchange	441
13.23	Sulfur and Soil Fertility Maintenance	442
13.24	Conclusion	442
	References	443
<b>14 SOIL PHOSPHORUS AND POTASSIUM</b>		<b>445</b>
14.1	Role of Phosphorus in Plant Nutrition and Soil Fertility	446
14.2	Effects of Phosphorus on Environmental Quality	447
14.3	The Phosphorus Cycle	452
14.4	Organic Phosphorus in Soils	456
14.5	Inorganic Phosphorus in Soils	459
14.6	Solubility of Inorganic Phosphorus in Acid Soils	463
14.7	Inorganic Phosphorus Availability at High pH Values	466
14.8	Phosphorus-Fixation Capacity of Soils	467
14.9	Practical Control of Phosphorus Availability	471
14.10	Potassium: Nature and Ecological Roles	473
14.11	Potassium in Plant and Animal Nutrition	473
14.12	The Potassium Cycle	475
14.13	The Potassium Problem in Soil Fertility	478
14.14	Forms and Availability of Potassium in Soils	480
14.15	Factors Affecting Potassium Fixation in Soils	483
14.16	Practical Aspects of Potassium Management	484
14.17	Conclusion	486
	References	486
<b>15 MICRONUTRIENT ELEMENTS</b>		<b>488</b>
15.1	Deficiency versus Toxicity	489
15.2	Role of the Micronutrients	490
15.3	Source of Micronutrients	491
15.4	General Conditions Conducive to Micronutrient Deficiency	494
15.5	Factors Influencing the Availability of the Micronutrient Cations	495
15.6	Organic Compounds as Chelates	500
15.7	Factors Influencing the Availability of the Micronutrient Anions	504
15.8	Need for Nutrient Balance	506
15.9	Soil Management and Micronutrient Needs	507
15.10	Conclusion	510
	References	511
<b>16 PRACTICAL NUTRIENT MANAGEMENT</b>		<b>512</b>
16.1	Goals of Nutrient Management	512
16.2	Environmental Quality	516

16.3	Nutrient Resources	520
16.4	Soil–Plant–Atmosphere Nutrient Cycles	521
16.5	Recycling Nutrients through Animal Manures	526
16.6	Storage, Treatment, and Management of Animal Manures	528
16.7	Industrial and Municipal By-Products	531
16.8	Sewage Effluent and Sludge	532
16.9	Practical Utilization of Organic Nutrient Sources	534
16.10	Integrated Recycling of Wastes	535
16.11	Inorganic Commercial Fertilizers	538
16.12	The Concept of the Limiting Factor	543
16.13	Fertilizer Application Methods	544
16.14	Timing of Fertilizer Application	549
16.15	Diagnostic Tools and Methods	551
16.16	Plant Symptoms and Field Observations	551
16.17	Plant Analysis and Tissue Testing	551
16.18	Soil Analysis	553
16.19	Broader Aspects of Fertilizer Practice	558
16.20	Conclusion	561
	References	561
<b>17 SOIL EROSION AND ITS CONTROL</b>		<b>563</b>
17.1	Significance of Runoff and Soil Erosion	563
17.2	Accelerated Erosion: Mechanics	567
17.3	Types of Water Erosion	568
17.4	Factors Affecting Accelerated Erosion: Revised Universal Soil-Loss Equation	569
17.5	Rainfall and Runoff Factor	570
17.6	Soil Erodibility Factor	571
17.7	Topographic Factor	572
17.8	Cover and Management Factor	572
17.9	Support Practice Factor	574
17.10	Calculating Expected Soil Losses	578
17.11	Sheet and Rill Erosion Control	578
17.12	Conservation Tillage Practices	579
17.13	Gully Erosion	585
17.14	Wind Erosion: Importance and Control	587
17.15	Soil-Loss Tolerance	592
17.16	Land Capability Classification	594
17.17	Conservation Treatment in the United States	597
17.18	Conclusion	599
	References	599
<b>18 SOILS AND CHEMICAL POLLUTION</b>		<b>601</b>
18.1	Toxic Organic Chemicals	601
18.2	Kinds of Pesticides	602
18.3	Behavior of Organic Chemicals in Soils	604
18.4	Effects of Pesticides on Soil Organisms	610
18.5	Bioremediation of Soils Contaminated with Organic Chemicals	612
18.6	Contamination with Toxic Inorganic Substances	614
18.7	Potential Hazards of Chemicals in Sewage Sludge	616
18.8	Reactions of Inorganic Contaminants in Soils	617
18.9	Prevention and Elimination of Inorganic Chemical Contamination	619
18.10	Landfills	621
18.11	Soils as Organic Waste Disposal Sites	623
18.12	Soil Salinity	625
18.13	Radionuclides in Soil	625

18.14	Radon Gas from Soils	627
18.15	Conclusion	627
	References	628
19	GEOGRAPHIC SOILS INFORMATION	630
19.1	Soil Spatial Variability in the Field	630
19.2	Techniques and Tools for Mapping Soils	633
19.3	Modern Technology for Soil Investigations	639
19.4	Remote Sensing Tools for Soils Investigations	641
19.5	Air Photos	641
19.6	Satellite Imagery	645
19.7	Soil Surveys	647
19.8	The County Soil Survey Report and Its Utilization	650
19.9	Geographic Information Systems	653
19.10	Conclusion	657
	References	657
20	SOILS AND THE WORLD'S FOOD SUPPLY	659
20.1	Expansion of World Population	660
20.2	Factors Affecting World Food Supplies	661
20.3	The World's Land Resources	661
20.4	Potential of Different Soil Orders	663
20.5	Problems and Opportunities in the Tropics	665
20.6	Shifting Cultivation	668
20.7	Requisites for the Future	672
20.8	Consequences of Food Production Success/Failure	677
20.9	Conclusion	677
	References	678
GLOSSARY	693	
INDEX	727	



# 1

## THE SOILS AROUND US

*If we take time to learn the language of the land,  
the soil will speak to us.*  
—R. WEIL AND W. KROONTJE, LISTENING TO THE LAND

The Earth, our unique home in the vastness of the universe, is in crisis. Depletion of the ozone layer in the upper atmosphere is threatening us with an overload of ultraviolet radiation. Tropical rain forests, and the incredible array of plant and animal species they contain, are disappearing at an unprecedented rate. Groundwater supplies are being contaminated in many areas and depleted in others. In parts of the world, the capacity of soils to produce food is being degraded, even as the number of people needing food is increasing. It will be a great challenge for the current generation to bring the global environment back into balance (Figure 1.1).

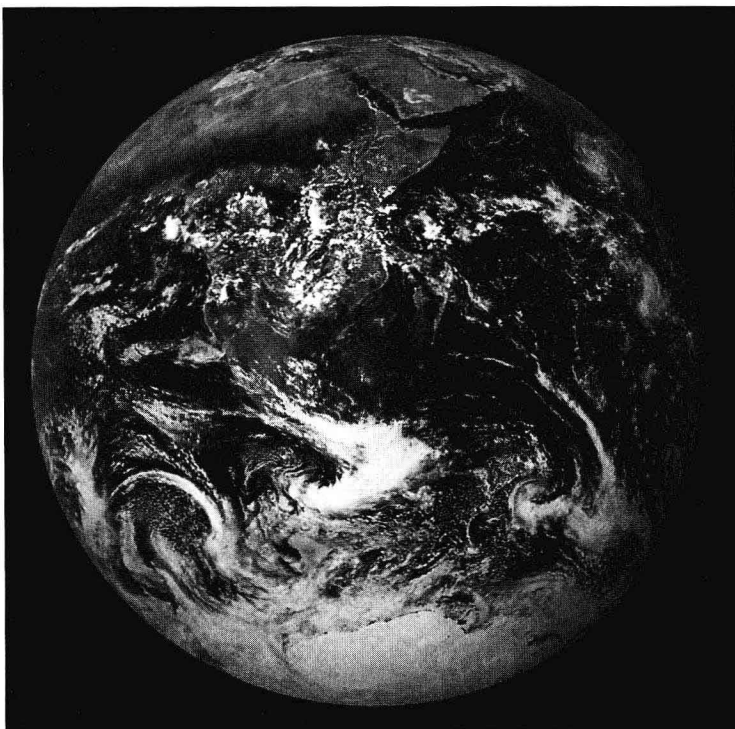


FIGURE 1.1 Our planet is unique in that it is covered with life-sustaining water and soil. Great care will be required in preserving the quality of both if our species is to continue to thrive. (Photo courtesy of NASA)

Soils are crucial to life on earth. From ozone depletion to rain forest destruction to water pollution, the global ecosystem is impacted in far-reaching ways by the processes carried out in the soil. To a great degree, soil quality determines the nature of plant ecosystems and the capacity of land to support animal life and society. As human societies become increasingly urbanized, fewer people have intimate contact with the soil, and individuals tend to lose sight of the many ways in which they depend upon soils for their prosperity and survival. The degree to which we are dependent on soils is likely to increase, not decrease, in the future. Of course, soils will continue to supply us with nearly all of our food and much of our fiber. On a hot day, would you rather wear a cotton shirt or one made of polyester? In addition, biomass grown on soils is likely to become an increasingly important source of energy and industrial feedstocks, as the world's finite supplies of petroleum are depleted over the coming century. The early signs of this trend can be seen in the soybean oil-based inks, the cornstarch plastics, and the wood alcohol fuels that are becoming increasingly important on the market (Figure 1.2).

The art of soil management is as old as civilization. As we move into the 21st century, new understandings and new technologies will be needed to protect the environment and at the same time produce food and biomass to support society. The study of soil science has never been more important to farmers, engineers, natural resource managers, and ecologists alike.

## 1.1 FUNCTIONS OF SOILS IN OUR ECOSYSTEM

In any ecosystem, whether your backyard, a farm, a forest, or a regional watershed, soils have five key roles to play (Figure 1.3). First, soil supports the growth of higher plants, mainly by providing a medium for plant roots and supplying nutrient elements that are essential to the entire plant. Properties of the soil often determine the nature of the veg-

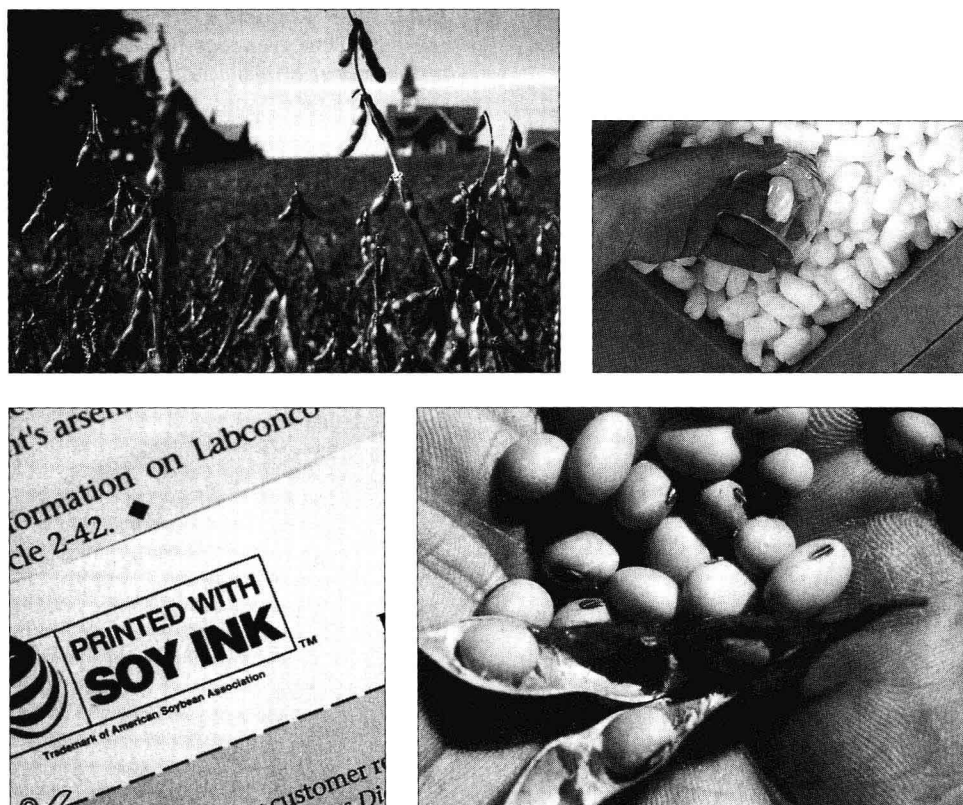


FIGURE 1.2 In the future, we will be increasingly dependent on soils to grow renewable resources that can substitute for dwindling supplies of crude oil. Plastics and inks, for example, can be manufactured from soybean seed oil instead of from petroleum. Soybean oil is edible and far less toxic to the environment. Plastics, such as packaging foam “peanuts,” made from cornstarch are readily biodegradable. (Photos courtesy of R. Weil)

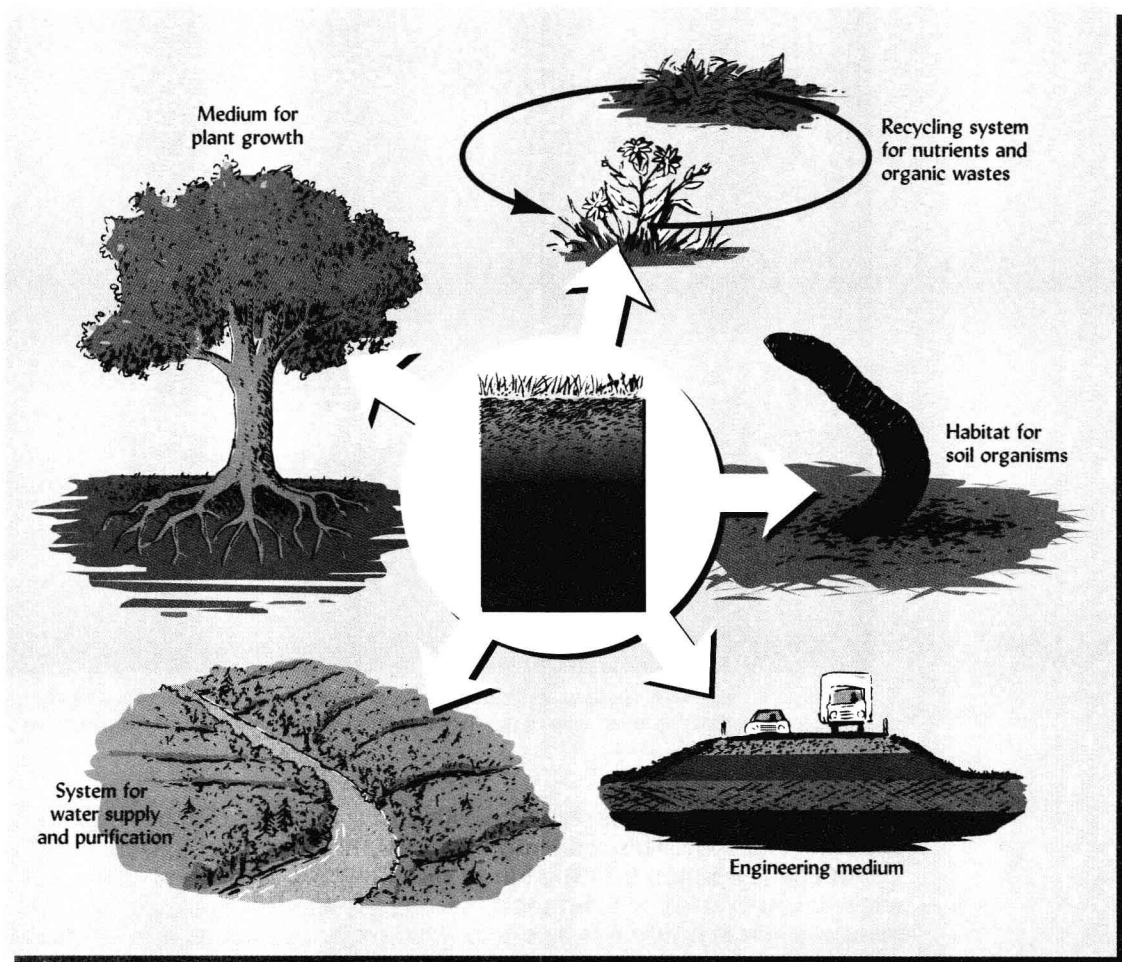


FIGURE 1.3 The many functions of soil can be grouped into five crucial ecological roles.

etation present and, indirectly, the number and types of animals (including people) that the vegetation can support. Second, soil properties are the principal factor controlling the fate of water in the hydrologic system. Water loss, utilization, contamination, and purification are all affected by 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. Fourth, soils provide habitats for a myriad of living organisms, from small mammals and reptiles to tiny insects to microscopic cells of unimaginable numbers and diversity. Finally, in human-built ecosystems, 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 MEDIUM FOR PLANT GROWTH

Imagine a growing tree or a corn plant. The aboveground portion of this plant may be most familiar, but the portion of the plant growing below the soil surface, its root system, may be nearly as large as the portion we see above ground. What things do these plants obtain from the soils in which their roots proliferate? It is clear that the soil mass provides physical support, anchoring the root system so that the plant does not fall over. Occasionally, as in Figure 1.4, plants will fall over during windy conditions if shallow soils or restrictive soil layers make them top-heavy.

Plant roots depend on the process of respiration to obtain energy. Since root respiration, like our own respiration, produces carbon dioxide ( $\text{CO}_2$ ) and uses oxygen ( $\text{O}_2$ ), an



**FIGURE 1.4** This wet, shallow soil failed to allow sufficiently deep roots to develop to prevent this tree from blowing over when snow-laden branches made it top-heavy during a winter storm. (Photo courtesy of R. Weil)

important function of the soil is “ventilation”—allowing  $\text{CO}_2$  to escape and fresh  $\text{O}_2$  to enter the root zone. This ventilation is accomplished via the network of soil pore spaces.

An equally important function of the soil pores is to absorb rainwater and hold it where it can be used by plant roots. As long as plant leaves are exposed to sunlight, the plant requires a continuous stream of water to use in cooling, nutrient transport, turgor maintenance, and photosynthesis. Since plants use water continuously, but it usually rains only occasionally, the water-holding capacity of soils is essential for plant survival. A deep soil may store enough water to allow plants to survive long periods without rain (see Figure 1.5).



**FIGURE 1.5** The mango tree in this central Africa field is in full leaf and beginning to flower, even though no rain had fallen for the five months prior to when this photograph was taken. The trees are still using water stored from the previous rainy season in this deep clayey soil. It is the local belief that abundant flowering on the mango tree presages a good rainy season to come. Note that the more shallow-rooted grasses growing in thinner soils on the hillside are in a light-colored, dried-up, dormant condition. (Photo courtesy of R. Weil)



As well as moderating moisture changes in the root environment, the soil also moderates temperature fluctuations. Perhaps you can recall digging in garden soil on a summer afternoon and feeling how hot the soil was at the surface and how much cooler just a few centimeters below. The insulating properties of soil protect the deeper portion of the root system from the extremes of hot and cold that often occur at the soil surface. For example, it is not unusual for the temperature at the surface of bare soil to exceed 35 or 40°C in midafternoon, a condition that would be lethal to most plant roots. Just a few centimeters deeper, however, the temperature may be 10°C cooler, allowing roots to function normally.

There are many potential sources of **phytotoxic substances** in soils. These toxins may result from human activity, or they may be produced by plant roots, by microorganisms, or by natural chemical reactions. Many soil managers consider a function of a good soil to be protection of plants from toxic concentrations of 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.

Soils supply plants with inorganic, mineral nutrients in the form of dissolved ions. These mineral nutrients include such metallic elements as potassium, calcium, iron, and copper, as well as such nonmetallic elements as nitrogen, sulfur, phosphorus, and boron (Table 1.1). The plant takes these elements out of the soil solution and incorporates most of them into the thousands of different organic compounds that constitute plant tissue. A fundamental role of soil in supporting plant growth is to provide a continuing supply of dissolved mineral nutrients in amounts and relative proportions appropriate for plant growth. While plants may use minute quantities of organic compounds from soils, uptake of these substances is certainly not necessary for normal 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.

It is true that plants can be grown in nutrient solutions without soil (**hydroponics**), but then the plant-support functions of soils must be engineered into the system and maintained at a high cost of time, effort, and management. Although hydroponic production can be feasible on a small scale for a few high-value plants, the production of the world's food and fiber and the maintenance of natural ecosystems will always depend on the use of millions of square kilometers of productive soils.

### 1.3 REGULATOR OF WATER SUPPLIES

There is much concern about the quality and quantity of the water in our rivers, lakes, and underground aquifers. Governments and citizens everywhere are working to stem

**TABLE 1.1 Elements Essential for Plant Growth and Their Sources<sup>a</sup>**

<i>Used in relatively large amounts (&gt;0.1% of dry plant tissue)</i>		<i>Used in relatively small amounts (&lt;0.1% of dry plant tissue)</i>
<i>Mostly from air and water</i>	<i>Macronutrients (from soil solids)</i>	<i>Micronutrients (from soil solids)</i>
Carbon (C)	Nitrogen (N)	Iron (Fe)
Hydrogen (H)	Phosphorus (P)	Manganese (Mn)
Oxygen (O)	Potassium (K)	Boron (B)
	Calcium (Ca)	Molybdenum (Mo)
	Magnesium (Mg)	Copper (Cu)
	Sulfur (S)	Zinc (Zn)
		Nickel (Ni)
		Chlorine (Cl)
		Cobalt (Co)

<sup>a</sup>Many other elements are taken up from soils by plants, but are not essential for plant growth. Some of these elements (such as sodium, silicon, iodine, fluorine, barium, and strontium) do enhance the growth of certain plants, but do not appear to be as universally required for normal growth as are the 18 listed in this table.