FUNDAMENTALS OF SOIL SCIENCE

SEVENTH EDITION

HENRY D. FOTH

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JOHN WILEY & SONS
New York Chichester Brisbane Toronto Singapore

Library of Congress Cataloging in Publication Data

Foth, H. D.
Fundamentals of soil science.

Includes bibliographies and index.
1. Soil science. I. Title.
S591.F67 1984 631.4 83-23383
ISBN 0-471-88926-1

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PREFACE

Over the past several decades there has been a rapid increase in the knowledge about soil science. This Seventh Edition was extensively revised to illustrate that increase. The soil orders of *Soil Taxonomy* are introduced in Chapter 1 and are integrated into the chapters that follow. The concept of cation exchange is introduced in Chapter 2 and is used throughout the text. The energy relationships of soil water are discussed in terms of water potentials, and the material on irrigation and salinity is expanded. Soil mineralogy is covered in a separate, updated chapter (Chapter 7); it includes a more unified treatment of clay structures. This is followed by Chapter 8 on soil chemistry, which includes a unified discussion of soil pH in terms of a continuum. The roles of exchangeable aluminum and oxidic clays are examined in detail. Chapters 9 to 14 have been thoroughly updated and have additional material on fertilizers. The last chapter is entirely new and deals with the world population-food-land problem.

Throughout the book, there is a greater emphasis on soils from a global perspective. The numerous nonagricultural illustrations on the role of soils have been retained.

Many of my colleagues have engaged me in discussions that have helped to clarify difficult concepts. Special thanks go to Nate Rufe and Lynn Foth, who printed the new photographs used in this edition, and to Mary Foth for the cover photograph.

East Lansing
Michigan

Henry D. Foth

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CHAPTER 1

CONCEPTS OF SOIL

SOIL: Can you think of a substance that has had more meaning for humanity? The close bond that ancient civilizations had with the soil was expressed by the writer of Genesis in these words:

> *the Lord God formed Man from the dust of the earth—and Man became a living being.*

There has been, and is, a reverence for soil or the earth. Someone has said that the fabric of human life is woven on earthen looms everywhere it smells of clay. Even today, most of the world's population are tillers of the soil and live close to the soil that they depend on for food and fiber (*see* Fig. 1-1).

Since the development of agriculture, the most important concept of soil has been the concept of soil as a natural medium for plant growth. When cities developed, soil became important as an engineering material to support roads and buildings. Now, soil serves many engineering uses, including landfills for waste disposal. The concept of soil as an engineering material is related to soil as a mantle of weathered rock or regolith—a concept developed by geologists in the late eighteenth century. Since the late nineteenth century, soil scientists developed the concept of soil as an *organized natural body.*

Figure 1-1
One half of the world's population are farmers who are closely tied to the land and make their living producing crops with simple tools.

Soil as an Organized Natural Body

The rapid accumulation of knowledge about soils during the nineteenth century created a need for a concept of soil that would accommodate the new facts. A revolutionary way of looking at soil was developed about 1870 in Russia by Dokuchaev. As he traveled about, he observed many different kinds of soils and noted that a given soil was found repeatedly in a given situation. Dokuchaev saw that each kind of soil had a unique morphology resulting from a unique combination of climate, living matter (plants and animals), earthy parent material, topography, and age of the land. The soil was the product of evolution and changed over time. This dynamic and evolutionary nature is embodied in a definition of soil as:

> *unconsolidated mineral matter on the surface of the earth that has been subjected to and influenced by genetic and environmental factors of:* parent material, climate *(including moisture and temperature effects),* macro- *and* micro-organisms, *and* topography, *all acting over a period of time and producing a product-soil-that differs from the material from which it is derived in many physical, chemical, and biological properties, and characteristics.*[1]

Soil Genesis Processes

Soils are products of evolution and have a unique organization consisting of genetically developed layers or horizons. Soil genesis or horizon development processes can be viewed as *additions, losses, transformations,* or *translocations.* Plants and animals find a habitat in all soils and become a part of the organic matter. Carbon in organic matter is lost from soil as carbon dioxide that results from microbial decomposition. Nitrogen is transformed from the organic to inorganic forms. Furthermore, organic matter is subject to translocation from place to place

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[1] From *Glossary of Soil Science Terms*. Soil Science Society of America, Madison, Wis., October, 1979.

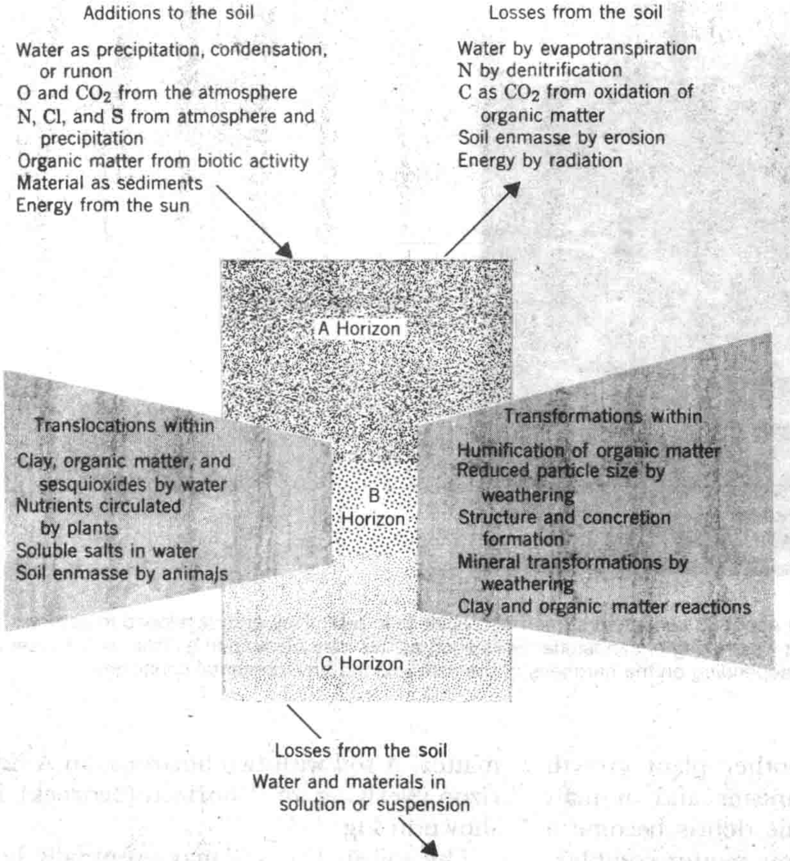

Figure 1-2
Diagrammatic presentation of additions, losses, translocations, and transformations involved in horizon differentiation.

in the soil by means of water and animal activity.

Mineral constituents undergo changes that can be similarly considered. In all soils, minerals weather with the simultaneous formation of secondary minerals and other compounds of varying solubility that may be moved from one horizon to another. In humid regions, water migrates down and through the soil and removes soluble material. Many soils receive additions of dust, volcanic ash, or sediments eroded from higher land. A summary of these processes is presented in Fig. 1-2.

Soil Horizon Evolution

Weathering of bedrock produces unconsolidated debris that serves as the *parent material* for the evolution of soils that eventually reflect the integrated effect of climate, living matter, relief, and time. Exposure of parent material to the weather, under favorable conditions, will result in the establishment of plants. Plant growth results in the accumulation of organic residues. Animals, bacteria, and fungi join the biological community and feed on these organic remains. Breakdown of organic matter sets free the nutrients con-

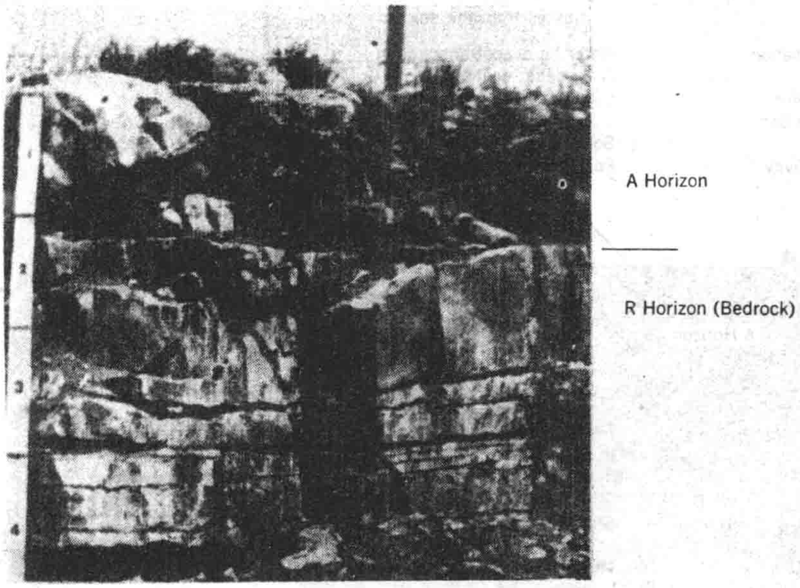

Figure 1-3
An AR soil. The A horizon is about 30 centimeters (or 1 foot, scale is in feet) thick and developed in parent material formed by the direct weathering of sandstone. Soils such as this may develop in as little as 100 years or 100,000 years or longer, depending on the hardness of the rock and the environmental conditions.

tained therein for another plant growth cycle. The microorganisms and animals feeding on the organic debris become a part of the total organic matter complex. When the surface layer attains a reasonable thickness and assumes a darkened color because of the accumulation of organic matter, an A *horizon* comes into existence. A soil horizon is a layer approximately parallel to the earth's surface that is the product of evolution; it has properties differing from adjacent horizons.

Soils developing under grass typically have thick, dark-colored A horizons that result from the profuse growth of roots to a considerable depth. In the forest, the addition of organic matter results largely from leaves and wood. The addition of leaves and wood on top of the soil promotes the development of a thin, dark-colored A horizon enriched with organic matter. A soil with two horizons, an A horizon overlying an R horizon (bedrock), is shown in Fig. 1-3.

The soil in Fig. 1-3 may eventually become over 100 centimeters thick[2] if the rate of soil removal by erosion is less than the rate of weathering that converts bedrock into soil-parent material. It appears, however, that most soils have formed in sediments produced by rock weathering and were transported to their present sites before the current cycle of soil formation began. Where soil evolution occurs in sediments, horizon evolution may proceed rapidly by comparison to evolu-

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[2] There are 2.54 centimeters per inch and 100 centimeters equals 1 meter, or 39.37 inches. For easy conversion, remember that 30 centimeters equals about 1 foot, and 1 meter is about equal to 1 yard. (*See* the table of conversion factors on the front inside cover of the book.)

Figure 1-4
Soil developed under forest with a thin A horizon that overlies E, B, and C horizons, respectively. The B horizon has been enriched with clay (Bt).

tion directly from hard bedrock. Pore spaces in sediments permit deep rooting by plants and facilitate removal of soluble compounds by percolating water. Suspended colloidal-sized particles are translocated by percolating water; however, the suspended colloidal particles tend to move only a short distance, commonly 15 to 50 centimeters, before the particles become lodged or precipitated. The process of deposition of material in a horizon that has been moved from some other horizon is *illuviation*. Illuviation, in this case, produces a zone under the A horizon where colloidal particles accumulate. This zone is designated the *B horizon*. The most common colloidal particles that accumulate in B horizons are clay, organic matter, and oxides of iron and aluminum (sesquioxides).

The translocation of colloids from the A horizon results in a concentration of sand and silt-sized particles of quartz and other resistant minerals in the upper part of many soils. In soils with thin A horizons, a lighter-colored layer, low in organic matter, may develop below the A horizon and above the B horizon. This horizon, commonly grayish in color, is the *E horizon*. The symbol E is derived from *eluvial*, meaning "washed out." Both A and E horizons are eluvial in a given soil, but the main feature of A is organic matter and a dark color, while that of E is a lighter color and concentration of silt and sand-sized particles of quartz and other resistant minerals.

The *C horizon* is a layer that is hardly affected by the soil-forming processes and lacks the properties of the other horizons. The C horizon commonly consists of sediments or material weathered directly from underlying bedrock. The most weathered upper soil horizons, above the C horizon, comprise the *solum*. A soil with A, E, B, and C horizons is shown in Fig. 1-4.

Master Soil Horizons

The master horizons are indicated by capital letters; the A, E, B, C, and R horizons have been described and their genesis discussed. In addition, there is the *O horizon*, which is dominated by organic matter. The mineral fraction is only a small percentage of the volume and generally much less than half the weight.

Some O horizons or layers such as muck and peat develop where the environment is water saturated for long periods of time. Much of the organic matter produced fails to decompose due to a lack of oxygen for organic matter decomposers. In forests of cold and humid regions, O horizons develop on top of the mineral soil horizons where conditions such as acidity and low temperature greatly inhibit organic matter decomposition.

Sometimes a soil horizon is dominated by the properties of one master horizon, but has the subordinate properties of another. Two capital letters are used, as in the case of AB. The first letter of AB indicates that the properties are more like the A than the B horizon. A hypothetical soil profile, with all master horizons and some transitional horizons, is shown in Fig. 1-5.

Subordinate Distinctions within Master Horizons. Lower case letters are used as suffixes to designate specific kinds of master horizons. The symbols and their meanings are as follows:

a—Highly decomposed organic material (contrast with e and i).

b—Buried genetic horizon.

c—Concretions or hard nonconcretionary nodules (iron, aluminum, manganese or titanium).

e—Organic material of intermediate decomposition.

f—Frozen soil (permanent ice).

g—Strong gleying (reduction of iron and other compounds and development of gray colors due to poor drainage).

h—Illuvial accumulation of organic matter.

i—Slightly decomposed organic material.

k—Accumulation of carbonates.

m—Cementation or induration.

n—Accumulation of sodium.

o—Residual accumulation of sesquioxides (mainly oxides of iron and aluminum).

p—Plowing or other disturbance.

q—Accumulation of silica.

r—Weathered or soft bedrock.

s—Illuvial accumulation of sesquioxides and organic matter.

t—Accumulation of silicate clay.

v—Plinthite (subsoil material enriched with iron becoming hard or bricklike due to repeated drying and wetting).

w—Development of color or structure.

x—Fragipan character (brittle with high bulk density).

y—Accumulation of gypsum.

z—Accumulation of salts more soluble than gypsum.

An example of the use of suffixes is the case of a Ckm horizon, which indicates a C horizon with an accumulation of carbonates that is cemented or indurated. The soil in Fig. 1-4 has a Bt horizon due to an illuvial accumulation of clay particles that have been moved downward from the A and E horizons. When more than one suffix is used, the following letters, if used, are written first: a, e, i, h, r, s, t, and w.

Soil Orders

There is great diversity among the soil-forming factors; the result is that hundreds of thousands of different soils have been recognized in the world. These soils are classified into orders. The order is the most general category of the soil

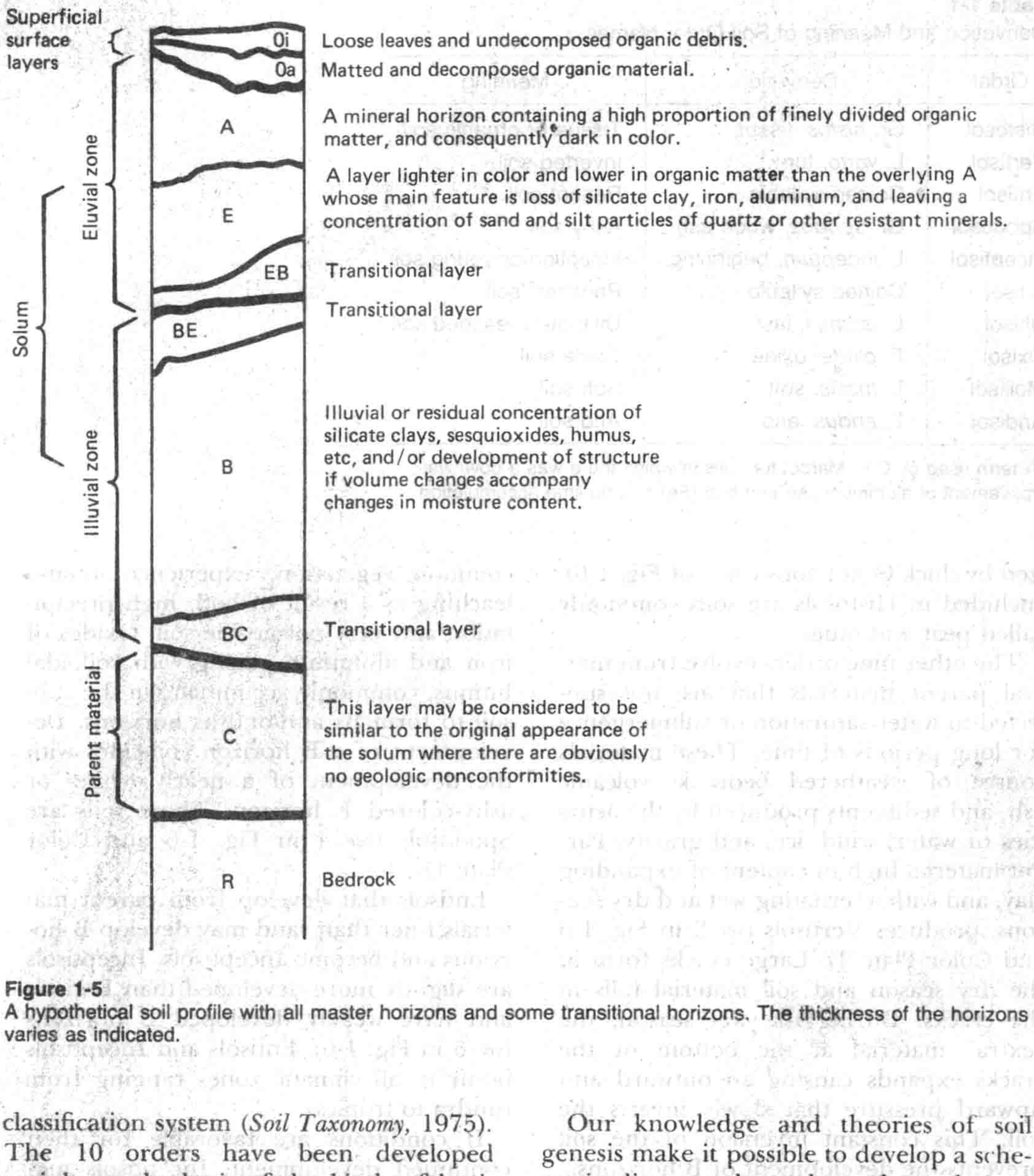

Figure 1-5
A hypothetical soil profile with all master horizons and some transitional horizons. The thickness of the horizons varies as indicated.

classification system (*Soil Taxonomy*, 1975). The 10 orders have been developed mainly on the basis of the kinds of horizons found in soils and the properties of these horizons. The soil order name consists of a prefix and ends with *sol*. The order names, their derivation, and meaning are given in Table 1-1.

Our knowledge and theories of soil genesis make it possible to develop a schematic diagram that relates the orders to the soil-forming factors as shown in Fig. 1-6. Histosols develop from organic parent materials that frequently form where the environment is water saturated, as in ponds and lakes. Histosols are character-

Table 1-1
Derivation and Meaning of Soil Order Names

Order	Derivation	Meaning
Histosol	Gr. *histos,* tissue	Tissue or organic soil.
Vertisol	L. *verto,* turn	Inverted soil
Entisol	Coined syllable	Recent soil
Spodosol	Gr. *spodos,* wood ash	Ashy soil
Inceptisol	L. *inceptum,* beginning	Inception or young soil
Alfisol	Coined syllable	Pedalfer[a] soil
Ultisol	L. *ultimus,* last	Ultimately leached soil
Oxisol	F. *oxide,* oxide	Oxide soil
Mollisol	L. *mollis,* soft	Soft soil
Aridisol	L. *aridus,* arid	Arid soil

[a] A term used by C.F. Marbut for soils in which there was a downward movement of aluminum (Al) and iron (Fe) and no lime accumulation.

ized by thick O horizons (*see* 1 of Fig. 1-6). Included in Histosols are soils commonly called peat and muck.

The other nine orders evolve from mineral parent materials that are not subjected to water saturation or submergence for long periods of time. These materials consist of weathered bedrock, volcanic ash, and sediments produced by the activities of water, wind, ice, and gravity. Parent material high in content of expanding clay, and with alternating wet and dry seasons, produces Vertisols (*see* 2 in Fig. 1-6 and Color Plate 1). Large cracks form in the dry season and soil material falls in the cracks. During the wet season, the "extra" material at the bottom of the cracks expands causing an outward and upward pressure that slowly inverts the soil. This constant inversion of the soil prevents the development of B horizons.

AC and AR soils develop from the other parent materials. These young or recent soils are Entisols (*see* 3 in Fig. 1-6). Entisols that are formed from quartzitic sand in humid regions, where forest is the common vegetation, experience intense leaching as a result of both high precipitation and very permeable soil. Oxides of iron and aluminum, along with colloidal humus, commonly accumulate in the subsoil to form Bs and/or Bhs horizons. Development of a B horizon coincides with the development of a nearly white- or ashy-colored E horizon. These soils are Spodosols (*see* 4 in Fig. 1-6 and Color Plate 1).

Entisols that develop from parent materials finer than sand may develop B horizons and become Inceptisols. Inceptisols are slightly more developed than Entisols and have weakly developed B horizons (*see* 5 in Fig. 1-6). Entisols and Inceptisols occur in all climatic zones ranging from tundra to tropics.

If conditions are favorable for their continued development, Inceptisols may develop into one of the other five orders. Alfisols develop in forested humid regions where clay migration produces a Bt horizon that has 20 percent or more clay than the A horizon, and the soil is only mod-

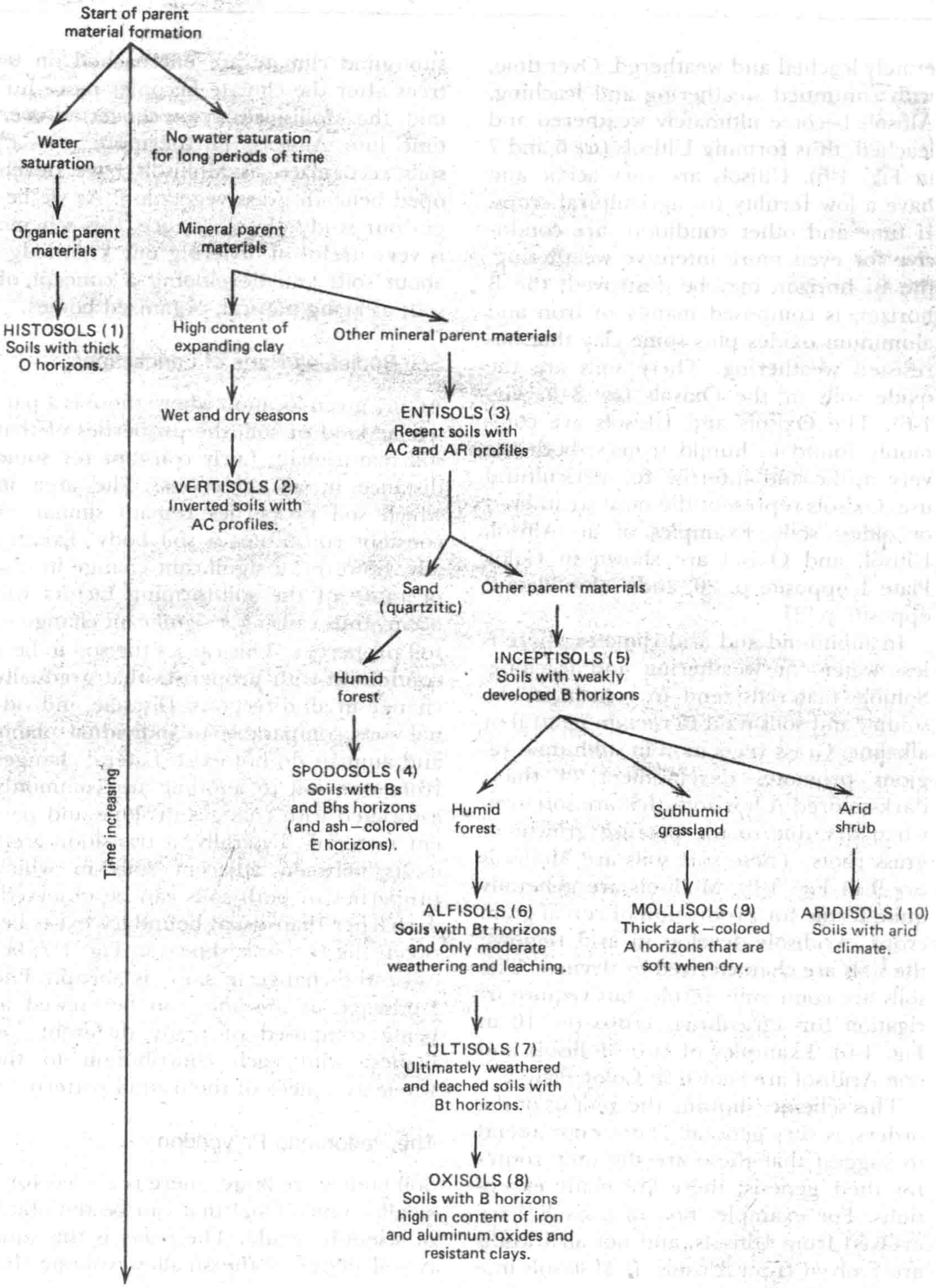

Figure 1-6
Major factors affecting the development of soil orders and some routes for their genesis.

erately leached and weathered. Over time, with continued weathering and leaching, Alfisols become ultimately weathered and leached, thus forming Ultisols (*see* 6 and 7 in Fig. 1-6). Ultisols are very acidic and have a low fertility for agricultural crops. If time and other conditions are conducive for even more intensive weathering, the Bt horizon may be destroyed; the B horizon is composed mainly of iron and aluminum oxides plus some clay that has resisted weathering. These soils are the oxide soils or the Oxisols (*see* 8 in Fig. 1-6). The Oxisols and Ultisols are commonly found in humid tropics; both are very acidic and infertile for agricultural use. Oxisols represent the most weathered or oldest soils. Examples of an Alfisol, Ultisol, and Oxisol are shown in Color Plate 1 opposite p. 20, and Color Plate 2 opposite p. 21.

In subhumid and arid climates, there is less water for weathering and leaching. Soluble materials tend to remain in the solum, and soils tend to remain neutral or alkaline. Grass vegetation in subhumid regions promotes development of thick, dark-colored A horizons that are soft even when dry due to the profuse growth of grass roots. These soft soils are Mollisols (*see* 9 in Fig. 1-6). Mollisols are generally quite fertile for production of cereal grain crops. Aridisols develop in arid regions; the soils are characterized by dryness. The soils are commonly fertile, but require irrigation for agricultural crops (*see* 10 in Fig. 1-6). Examples of two Mollisols and one Aridisol are shown in Color Plate 2.

This scheme, showing the genesis of the orders, is very general. It does not intend to suggest that these are the only routes for their genesis; there are many exceptions. For example, not all Oxisols have evolved from Ultisols, and not all Ultisols are evolved from Alfisols. If Mollisols in a subhumid climate are encroached on by trees after the climate becomes more humid, the Mollisols may be converted over time into Alfisols. Furthermore, not all soils recognized as Mollisols have developed beneath grass vegetation. As we begin our study of soil science, this scheme is very useful in ordering our knowledge about soils and developing a concept of soils as being natural, organized bodies.

Soil Bodies as Parts of Landscapes

At any given location where there is a particular kind of soil, the properties of that soil may remain fairly constant for some distance in all directions. The area in which soil properties remain similar or constant constitutes a soil body. Eventually, however, a significant change in one or more of the soil-forming factors will occur, thus causing a significant change in soil properties. This causes the soil to be a continuum with properties that gradually change in all directions. Discrete, individual soils comparable to individual plants and animals do not exist. Lateral changes from one soil to another are commonly associated with changes in slope and parent material. Typically, a transition zone exists between adjacent soils in which properties of both soils can be observed. A sharper than usual boundary exists between the two soils shown in Fig. 1-7, because the change in slope is abrupt. The landscape as a whole can be viewed as being composed of many different soil bodies; with each contribution to the whole as a piece of the overall pattern.

The Pedon and Polypedon

Soil bodies are large; there is a need for a smaller unit of soil that can be the object of scientific study. The *pedon* is this unit. A soil pedon is the smallest volume that