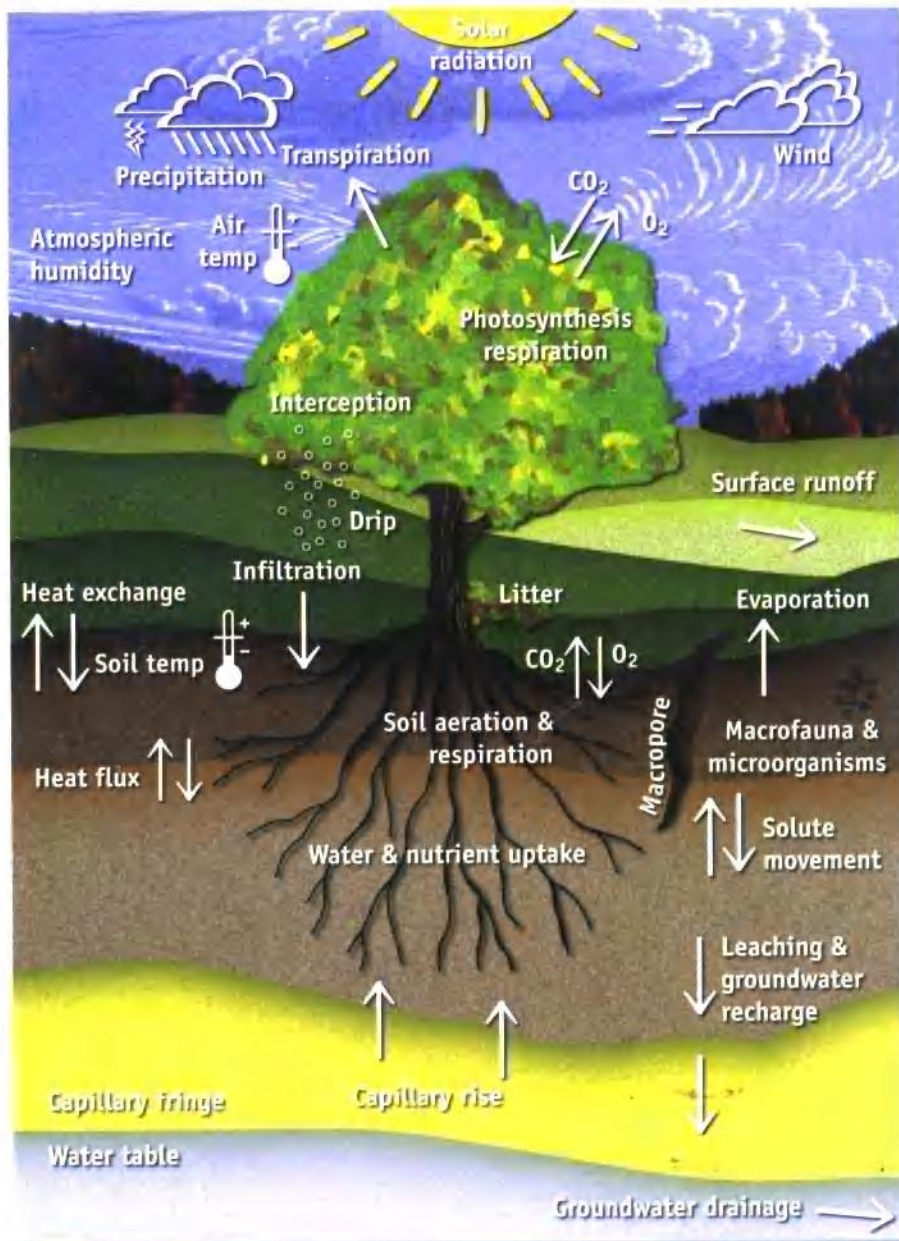


Environmental Soil Physics



DANIEL HILLEL

ENVIRONMENTAL SOIL PHYSICS

Daniel Hillel

*Professor Emeritus
Plant, Soil, and Environmental Sciences
University of Massachusetts
Amherst, Massachusetts*

With Contributions by

A. W. Warrick


R. S. Baker

C. Rosenzweig



ACADEMIC PRESS

San Diego London Boston New York Sydney Tokyo Toronto

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Academic Press
a division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, CA 92101-4495, USA
<http://www.apnet.com>

Academic Press
24–28 Oval Road, London NW1 7DX, UK
<http://www.hbuk.co.uk/ap/>

Library of Congress Cataloging-in-Publication Data

Hillel, Daniel.

Environmental soil physics / Daniel Hillel.

p. cm.

Includes bibliographical references (p.) and index.

ISBN 0-12-348525-8

1. Soil physics. 2. Soil physics—Environmental aspects.

I. Title.

S592.3.H535 1998

631.4—dc21

98-23679

CIP

Printed in the United States of America

98 99 00 01 02 IP 9 8 7 6 5 4 3 2 1

ENVIRONMENTAL SOIL PHYSICS

*I dedicate this book to my wife,
Professor Michal Artzy,
for all she has done, and does, and is.*

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*Then the Lord God fashioned the earthling [ha-adam]
from the soil of the earth [ha-adama],
and breathed into his nostrils the breath of life,
so the earthling became a living soul.*

—Genesis 2:7

FOREWORD

The Biblical depiction of humanity's advent, cited above, reveals a profound insight that modern civilization is in grave danger of forgetting. Our innate and indissoluble attachment to the soil is manifest in the designation of the first human being, derived from *adama*, a Hebrew noun of feminine gender meaning “earth,” or “soil.” The originally formed (Genesis 2:7) earthling, *ha-adam* (“the adam,” implying “of the soil”), was later (Genesis 2:22) differentiated into a man and a woman, respectively named Adam and Hava, who were said to be the progenitors of all the divergent peoples inhabiting the planet. Adam's name encapsulates humanity's inception and destiny: our existence and livelihood derived from the soil, to which we are tethered throughout our lives and to which we are fated to return at the end of our days. The name of Adam's mate, Hava (rendered Eva or Eve in transliteration), itself means “living,” or “life-giving.” The coupling of Adam and Eve, therefore, signifies quite literally the mutual dependence of soil and life.

The same powerful metaphor is echoed in the Latin name for man—*homo*—derived from *humus*, the living material of the soil. Hence, the adjective “human” also implies “of the soil.” Other ancient cultures evoked equally powerful associations and feelings of reverence toward the earth. To the ancient Greeks, the earth was Gaea, the great maternal goddess who, impregnated by Uranus (god of the sky), gave birth to all the gods of the Greek pantheon. Her name is embedded in such modern terms as *geology*, *geophysics*, and *geponics* (the science of agriculture), and even in the prevalent name George (derived from *geo+ergon*, meaning “working the soil”). One of Gaea's descendants was Demeter, the earth goddess whose spirit was believed to

reside in sacred rocks, springs, and caves. The Romans identified her with their goddess of agriculture, Ceres, whose name was transmuted into “cereal” (edible grain) and whose main festival—the Cerealia—was celebrated in springtime. In the teachings of Buddha, as well as in the traditions of Africans, Native Americans, and Australian aborigines, the earth was revered as the source of fertility, the site of germination and regeneration, indeed the womb of terrestrial life.

The earth (encompassing the soil in its larger environmental context) played such an important role in ancient mythology for a very compelling reason: Our early forebears lived in intimate contact with the earth and experienced its phenomena directly. They felt the unmitigated lash of hailstorms and gale-force winds, bore the brunt of droughts, and suffered the fury of floods. They cleared and tilled the land, sowed seeds and planted saplings in the soft soil, and saw the pelting raindrops slake the clods and the harsh sun drying and cracking the bare surface. They prayed for gentle rains that would keep the soil from either desiccating or eroding, and nurtured their crops with tender care. They stored their harvested grain in earthen pits, built mud houses, and discovered that clay could be baked to form a new and lasting material—called *ceramic*—from which they could fashion pots for food and tablets for writing. Throughout their lives, they were grateful for the earth’s bounty without ever taking it for granted. People living on the land depended utterly on their knowledge of the soil in the constant endeavor to derive their sustenance from it.

Our civilization depends on the soil more vitally than ever, because our numbers have grown while available soil resources have diminished and deteriorated. Paradoxically, however, even as our dependence on the soil has increased, most of us have become physically and emotionally detached from it. The majority of the people in the so-called “developed” countries spend their lives in the artificial environment of a city, insulated from direct exposure to nature. Some city dwellers try to grace their homes with ornamental plants that are made to grow in sterile media rather than real soil. Many children assume that food originates in supermarkets. Few people now pray for rain, and many consider it merely a nuisance.

Detachment has bred ignorance, and out of ignorance has come the delusion that our civilization has risen above nature and set itself free of its constraints. Agriculture and food security, erosion and salination, degradation and destruction of natural ecosystems, disposal of waste products, depletion and pollution of surface waters and aquifers, and trends affecting the quality of the local and of the global environment—all of these processes, which involve the soil either directly or indirectly—have become mere abstractions to the majority of our people. The very language we use betrays a disdain for that common material underfoot, often referred to as “dirt.” Some fastidious parents prohibit their children from playing in the mud and hurry to wash their “soiled” hands when the children nonetheless obey an inherent instinct to do so. Thus is devalued and treated as unclean what is in fact the terrestrial realm’s principal medium of purification, wherein wastes are decomposed and nature’s productivity is continually restored.

Obviously, modern society cannot manage efficiently and sustainably what too many, including policymakers both national and international, do not

know and therefore do not care about (nor take care of). Ignorance of the terrestrial environment, at the core of which lies the soil, leads to further mismanagement and abuse. That is why one of the major tasks of our age is to generate and disseminate sound knowledge of environmental domains and processes, especially as these are threatened—however inadvertently—by human action.

A romantic poet gazing through a window at a green field (depicted on the book's cover) might view it as a place of idyllic serenity. Not so an environmental soil physicist, who discerns not rest but unceasing turmoil, a seething foundry in which matter and energy are in constant flux. Radiant energy from the sun streams onto the field, and as it cascades through the atmosphere-vegetation-soil-subsoil continuum it induces a complex sequence of processes: Heat is exchanged; water percolates through the intricate passages of the soil; plant roots suck up that water and transmit it through the stems to the leaves, which transpire it back to the atmosphere. The leaves absorb carbon dioxide from the air and synthesize it with soil-derived water to form the primary compounds of life. Oxygen emitted by those leaves makes the air breathable for animals, which consume and in turn fertilize the plants. Myriads of organisms residing in the soil recycle the residues of both plants and animals, thus releasing nutrients that enhance fertility and spur regrowth.

The crucible of this foundry is the soil, a rich mix of mineral particles, organic matter, gases, and soluble compounds, which, when infused with water, constitutes a substrate for the initiation and maintenance of plant and animal life. The soil is thus a self-regulating biophysical factory, utilizing its own materials, water, and solar energy. It also determines the fate of rainfall and snowfall reaching the ground surface—whether the water thus received will flow over the land as runoff, causing flash floods, or seep downward to the subterranean reservoir called groundwater, which in turn maintains the steady flow of springs and streams. With its finite capacity to absorb and store moisture, the soil buffers and regulates all of these phenomena. Without the soil as an intermediary, rain falling over the continents would run off immediately, producing episodic violent floods, rather than sustained stream flow.

Considering the height of the atmosphere, the thickness of the earth's lithosphere, and the depth of the ocean, we note that the soil is an amazingly thin body—typically not much more than 1 meter in depth and often less than that. Yet it is the core and crux of terrestrial life. The ability of the soil to retain moisture (and nutrients) serves to bridge the gap between plant requirements, which are practically incessant, and the supply of freshwater by rainfall, which tends to be intermittent and irregular. The volume of moisture retained in the soil at any time, though seemingly small, greatly exceeds the volume in all the world's rivers.

The normally loose and porous condition of the soil allows the living roots of plants to penetrate and ramify within it so as to obtain anchorage and sustenance, and to extract stored moisture during dry spells between rains. But the soil is a leaky reservoir that loses water downward by seepage and upward by evaporation. Managing the system so as to ensure the survival of native vegetation as well as to maximize water-use efficiency by crops requires monitoring the balance of incoming versus outgoing water and the consequent

change of moisture storage (as well as nutrient storage) in the root zone. This demands not merely a qualitative understanding of the mechanisms involved, but also a precise quantitative knowledge of the rates and directions of all relevant processes.

However unique in form and function, the soil is not an isolated body. It is, rather, a central link in the larger chain of interconnected domains and processes comprising the terrestrial environment. The soil interacts both with the overlying atmosphere and the underlying strata, as well as with surface and underground bodies of water. Especially important is the interrelation between the soil and the microclimate. In parallel with its self-regulating function as a multivalve system shunting the flow of precipitated water in various directions, the soil also partitions energy among different processes. Radiation reaching the field is partly reflected and partly absorbed, depending on surface conditions. The energy absorbed is, in turn, transformed in part into soil heat (which then warms the overlying air) and in part into the latent heat of evapotranspiration (the sum of evaporation directly from the soil surface and transpiration from plants growing in the soil and drawing water from its interior). Only a minute fraction of the incoming solar energy goes to photosynthesis, which nonetheless is the most crucial process of all agriculture, indeed of the entire biological cycle.

The soil naturally acts as a living filter, in which pathogens and toxins that might otherwise foul the terrestrial environment are rendered harmless and transmuted into nutrients. Since time immemorial, humans and other animals have been dying of all manner of diseases and have then been buried in the soil¹ yet no major disease is transmitted by it. The term *antibiotic* was coined by the soil microbiologists who, as a consequence of their studies of soil bacteria and actinomycetes, discovered streptomycin (an important cure for tuberculosis and other infections). Ion exchange, a useful process of water purification, was also discovered by soil scientists studying the passage of solutes through beds of clay.

Modern society, however, generates ever greater quantities of potentially toxic residues and waste products, some of which do not occur naturally. The problem of how to dispose of domestic and industrial wastes safely has become acute in recent decades. Consequently, interest has arisen in the possibilities and limitations of applying various waste materials to the land so as to utilize the soil's ability to filter, retain, buffer, immobilize, decompose, or otherwise mitigate the hazards of polluting agents. Some proponents have credited the soil with amazing, even mystical, capacities to purify contamination. This is a dangerous notion. In fact, the soil has a significant but limited capacity to process pollutants. When that capacity is overtaxed, the soil may become merely a way station in the transmission of pollutants to water resources as well as directly to growing plants and thence to the biological food chain. The processes involved include physical transport phenomena, as well as complex

¹ In the words of Emily Bronte (1818–1948): “I listened to the soft wind breathing through the grass, and wondered . . . for the sleepers in that quiet earth.”

chemical and microbiological interactions that take place primarily in the upper layer of the soil.

Soil physics is the branch of soil science dealing with the physical properties of the soil, as well as with the measurement, prediction, and control of the physical processes taking place in and through the soil. Just as physics in general deals with the forms and interactions of matter and energy, so soil physics deals specifically with the state and movement of matter and with the transformations and fluxes of energy in the soil.

On the one hand, the fundamental study of soil physics aims at understanding of the mechanisms governing the behavior of the soil and its role in the biosphere, including such interrelated processes as the terrestrial energy exchange and the cycles of water and transportable materials in the field. On the other hand, the practice of soil physics aims at the proper management of soil by means of irrigation, drainage, soil and water conservation, tillage, aeration, and the regulation of soil temperature, as well as the response of soil bodies to mechanical stresses and the fate of various solutes in the soil.

Soil physics is thus both a basic and an applied science with a very wide range of interests, some of which are shared by other branches of soil science and by such interrelated sciences as geology, terrestrial ecology, hydrology, microclimatology, sedimentology, botany, and agronomy. Soil physics is also closely related to the engineering profession of soil mechanics, which deals with the soil as a construction and support material.

The task of soil physics is made difficult by the enormous and baffling intricacy of a medium containing myriads of mineral and organic components, all irregularly fragmented and variously associated in a geometric pattern that is so complex and labile as to challenge our imagination and descriptive powers. Some of the solid material consists of crystalline particles, while some is made up of amorphous gels that may coat the crystals and modify their behavior. The solid phase in the soil interacts with the fluids, water and air, that permeate soil pores. The entire soil is hardly ever in equilibrium, as it alternately wets and dries, swells and shrinks, disperses and flocculates, hardens and softens, warms and cools, freezes and thaws, compacts and cracks, absorbs and emits gases, adsorbs and releases exchangeable ions, precipitates and dissolves salts, becomes acidic or alkaline, and exhibits aerobic or anaerobic conditions leading to chemical oxidation or reduction.

To serve as a favorable medium for plant growth, the soil must not only store water and nutrients in available forms but must also be free of toxic factors. The soil–water–vegetation system is further complicated by the fact that plant roots must respire constantly and that most terrestrial plants cannot transfer oxygen from their aerial parts to their roots at a rate sufficient to provide for root respiration. Hence the soil itself must be well aerated, by the continuous exchange of oxygen and carbon dioxide between its pores and the external atmosphere. An excessively wet soil will stifle the roots of sensitive plants just as an excessively dry soil will desiccate them.

These are but a few of the issues confronting the relatively young science of soil physics, a field of study that has really come into its own only in the last few decades. Its rather late development is evidently due to the inherently complex nature of the system it attempts to study. Because the soil is not an

isolated medium but is in constant dynamic interaction with the larger environment, soil physics is also an aspect of the more encompassing field of environmental physics (sometimes called biospheric physics) and of the overall science of geophysics.

The early soil physicists were interested primarily in the agricultural aspects of their discipline, hence their research focused on the soil as a medium for the production of crops (including tillage and improvement of soil structure, moisture conservation in rainfed farming, and optimal management of irrigation and drainage). Recent decades have witnessed an increasing emphasis on the environmental aspects and applications of soil physics. Consequently, research in soil physics has expanded its scope to include problems related to natural ecosystems and to processes affecting the chemical pollution of the environment. Processes occurring in the soil are now seen to affect much more than the on-farm production of crops. Indeed, soil processes affect the entire terrestrial environment, including the local and regional climate, the natural food chain, biodiversity, and the fate of the numerous waste products of our civilization (among which are numerous pathogenic and toxic agents). Increasingly, the main concern of soil physics has shifted from the laboratory to the field, and from a one-dimensional to a multi-dimensional view interfacing with the domains of sister disciplines such as meteorology and climatology, hydrology, ecology, and geochemistry. The larger domain of soil physics encompasses greater complexity and variability in space and time, the treatment of which requires reliance on stochastic as well as deterministic methods.

Because of the complexity of the soil, we find it practically impossible to define completely its exact physical state at any time. In dealing with any particular problem, therefore, we are generally obliged to simplify our approach by concentrating on the factors that appear to have the greatest and most direct bearing on the problem at hand. We thereby choose to disregard as “extraneous complications” the factors that may seem to be of secondary importance.

In many cases, accordingly, the theories and equations employed in soil physics describe not the soil itself, but some ideal and well-defined model that we conjure up to simulate some aspect of the soil’s behavior. Thus, to cite a few examples, the soil may be represented at times by a collection of small spheres, and at other times by a bundle of capillary tubes, or a stack of parallel colloidal platelets, or a homogeneous mechanical continuum. Similarly, the soil is often represented as unidimensional and homogeneous, whereas in fact it is multi-dimensional and heterogeneous.

The value of each of these models depends on the degree of approximation or of realism with which the model portrays the relevant phenomena in specific cases. However, even at best such models cannot provide anything but a partial portrayal of soil behavior. Complications that we may choose to ignore at any moment do not in fact disappear. Having once defined the most important (or “primary”) effects, we soon discover that our model needs further refinement. So we then consider additional (“secondary” or “tertiary”) effects, and so on *ad infinitum*. Our developing knowledge of the soil, as of other complex systems, is gained by successive approximations. The practice of science is a persistent and painstaking endeavor to achieve a fuller comprehension of

observable phenomena without ever resting on yesterday's conclusions. Consequently, a valid book on environmental soil physics should reflect the complexity of the system even while attempting to present a coordinated and logical description of what is admittedly a still-evolving body of knowledge.

This book is an expansion of my earlier texts titled *Fundamentals of Soil Physics* and *Applications of Soil Physics*, published by Academic Press in 1980. The passage of time and the rapid progress of research now require supplanting those books with a fresh exposition of soil physics that will not only update the topics covered originally but also enlarge the scope of the field to cover environmental aspects that were either absent or only cursorily mentioned before.² While attempting to present a coordinated and logical description of what we know about the soil system and its interactions with the contiguous subterranean and atmospheric domains, however, we must also show where our current knowledge is still incomplete. Natural science in general has been excessively compartmentalized. Rather than concentrate exclusively on specific domains, we need to explore the neglected boundaries along which contiguous domains interact and interconnect within their larger context. Our science will progress by devoting ever greater attention to details while simultaneously striving to expand our sphere of inclusion in order to achieve a more encompassing view of the soil's role in terrestrial ecosystems.

Throughout the writing of this book, I have endeavored to make the exposition as accessible and as understandable as possible by explaining each development explicitly without assuming anything more than general undergraduate knowledge of the basic concepts of calculus, physics, chemistry, and biology. To make the book as autonomous and self-sustaining as possible, I have tried to avoid the use of unnecessary technical jargon or unfamiliar notation. Whenever necessary, I have made reference to outside sources for supplementary study. To help students to translate the abstractions of unfamiliar theory into actual working knowledge, I have presented sample problems in each chapter. These are worked out in a step-by-step manner, for the purpose of facilitating self-study.

A textbook on so vital a subject ought by right to capture and convey the special sense of wonderment and excitement that impels the scientist's quest to comprehend the workings of nature, and hence should give some pleasure in the reading. It is my hope that this book might indeed be read, not merely consulted, that its readers might find in it a few insights as well as facts, and that it will deepen their understanding as well as broaden their knowledge.

*We shall not cease from exploring
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.*

—T. S. Eliot, 1888–1965, “Four Quartets”

² A venerable professor of soil physics was once visited by a former student some twenty years after graduation. The student noted with surprise that the professor was administering a test with the same old questions. On being asked why, the professor replied, “The questions are still the same, but now the answers are different!”



Ancient Egyptian depiction of sowing and plowing. Tomb of Nakht, 18th Dynasty

ACKNOWLEDGMENTS

I am grateful to Dr. Zvi Ruder of Academic Press, for his faith and perseverance as he encouraged me to undertake the preparation of this tome; and to Assistant Production Manager Ms. Diane Grossman for guiding the critical transition from manuscript to final publication. I am likewise grateful to Mr. Jose Mendoza of the Goddard Institute for computerizing and improving the illustrations. Finally, I thank my colleague Dr. Cynthia Rosenzweig for her generous help and caring counsel in the making of this book.

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