FOURTH EDITION

BUILDING SOILS FOR BETTER CROPS

ECOLOGICAL MANAGEMENT FOR HEALTHY SOILS

FRED MAGDOFF
and HAROLD VAN ES

SARE
Sustainable Agriculture
Research & Education
HANDBOOK 10

BUILDING SOILS FOR BETTER CROPS

ECOLOGICAL MANAGEMENT FOR HEALTHY SOILS

FOURTH EDITION

BY FRED MAGDOFF AND HAROLD VAN ES

HANDBOOK SERIES BOOK 10

Published in 2021 by the Sustainable Agriculture Research and Education (SARE) program, with funding from the National Institute of Food and Agriculture, U.S. Department of Agriculture.

This book was published by Sustainable Agriculture Research and Education (SARE), supported by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture under award number 2019-38640-29881. USDA is an equal opportunity employer and service provider.

To order:
Visit www.sare.org/bsbc or call (301) 374-9696. Discounts are available for orders in quantity.

Library of Congress Cataloging-in-Publication Data

Names: Magdoff, Fred, 1942-, author. | Van Es, Harold, 1958-, author. | Sustainable Agriculture Research & Education (Program) | National Institute of Food and Agriculture (U.S.)
Title: Building soils for better crops : ecological management for healthy soils / by Fred Magdoff and Harold van Es.
Other titles: Ecological management for healthy soils | Sustainable Agriculture Network handbook series ; bk. 10.
Description: Fourth edition. | College Park : Sustainable Agriculture Research & Education, 2021. | Series: Handbook series ; bk. 10 | "This book was published by Sustainable Agriculture Research and Education (SARE), supported by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture under award number 2019-38640-29881" -- t.p. verso. | Includes bibliographical references and index. | Summary: "Building Soils for Better Crops is a one-of-a-kind, practical guide to ecological soil management. It provides step-by-step information on soil-improving practices as well as in-depth background-from what soil is to the importance of organic matter. Case studies of farmers from across the country provide inspiring examples of how soil and whole farms have been renewed through these techniques. A must-read for farmers, educators and students alike"-- Provided by publisher.
Identifiers: LCCN 2021018006 | ISBN 9781888626193 (paperback)
Subjects: LCSH: Soil management. | Humus.
Classification: LCC S592.8 .M34 2021 | DDC 631.4--dc23
LC record available at https://lccn.loc.gov/2021018006

Authors: Fred Magdoff and Harold van Es
Production Manager: Andy Zieminski
Copy Editing: Lizi Barba
Contributing Writers (farmer case studies): Lizi Barba, Amy Kremen and Laura Barrera
Graphic Design: Peggy Weickert, University of Maryland Design Services
Cover Illustration: Chris Johnson, Kite String Design
Cover Photo: Brandon O'Connor, USDA NRCS
Indexing: Linda Hallinger
Printing: University of Maryland Printing Services

CONTENTS

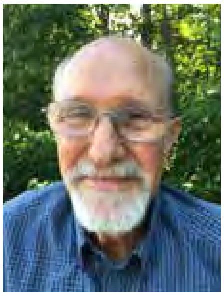
PART ONE ORGANIC MATTER—THE KEY TO HEALTHY SOILS

PART TWO PHYSICAL PROPERTIES AND NUTRIENT CYCLES AND FLOWS

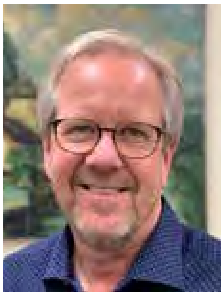
PART THREE ECOLOGICAL SOIL MANAGEMENT

PART FOUR PUTTING IT ALL TOGETHER

ABOUT THE AUTHORS



Fred Magdoff is emeritus professor of plant and soil science at the University of Vermont. He was Plant and Soil Science Department chair for eight years and for two decades was the coordinator of the 12-state Northeast Region for the U.S. Department of Agriculture's Sustainable Agriculture Research and Education (SARE) program. He is also a fellow of the American Society of Agronomy and the 2016 recipient of the Presidential Award of the Soil Science Society of America "for outstanding influence on soil science and enduring impact on the future of our science and profession." He has worked on soil testing for nitrogen and phosphorus, the effects of manures on soil properties and crop yields, buffering of soil pH, and many other issues related to soil health. He lives in Burlington and Fletcher, Vt., with his wife, two dogs, a large garden, an occasional flock of chickens and a small herd of beef cows.



Harold van Es is professor of soil science at Cornell University and served as chair of the Department of Crop and Soil Sciences. Born in Amsterdam, Netherlands, he moved to the United States for graduate studies and eventually a life and career in science. His current research, teaching and Extension efforts focus on soil health, digital agriculture and environmental statistics. He co-developed the widely used CASH soil health test and was the lead inventor of the Adapt-N technology, which was successfully commercialized and received the $1 million prize for the Tulane Nitrogen Reduction Challenge. He was the 2016 president of the Soil Science Society of America and is also a fellow of that society, as well as a fellow of the American Society of Agronomy. He and his wife live in Lansing, N.Y., where they raised three children.

SARE
Sustainable Agriculture
Research & Education

ABOUT SARE

Sustainable Agriculture Research and Education (SARE) is a grant-making and outreach program. Its mission is to advance—to the whole of American agriculture—innovations that improve profitability, stewardship and quality of life by investing in groundbreaking research and education. Since it began in 1988, SARE has funded more than 7,500 projects around the nation that explore innovations—from rotational grazing to direct marketing to cover crops—and many other best practices. Administering SARE grants are four regional councils composed of farmers, ranchers, researchers, educators and other local experts. SARE-funded Extension professionals in every state and island protectorate serve as sustainable agriculture coordinators who run education programs for agricultural professionals. SARE is funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture.

SARE GRANTS

www.sare.org/grants/apply-for-a-grant

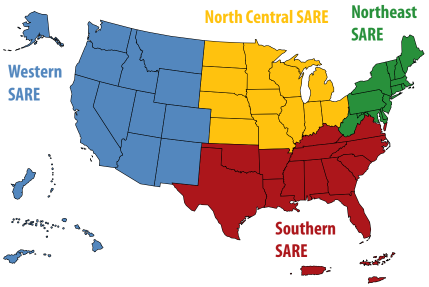
SARE offers several types of competitive grants to support the innovative applied research and outreach efforts of key stakeholders in U.S. agriculture. Grant opportunities are available to farmers and ranchers, scientists, Cooperative Extension staff and other educators, graduate students, and others. Grants are administered by SARE's four regional offices.

RESOURCES AND EDUCATION

www.sare.org/resources

SARE Outreach publishes practical books, bulletins, online resources and other information for farmers and ranchers. A broad range of sustainable practices are addressed, such as cover crops, crop rotation, diversification, grazing, biological pest control, direct marketing and more.

SARE REGIONS



SARE's four regional offices and outreach office work to advance sustainable innovations to the whole of American agriculture.

PREFACE

Used to be anybody could farm. All you needed was a strong back … but nowadays you need a good education to understand all the advice you get so you can pick out what'll do you the least harm.

—VERMONT SAYING, MID-1900s

We have written this book with farmers, farm advisors, students and gardeners in mind, although we have also found copies of earlier editions on the bookshelves of many of our colleagues in science. *Building Soils for Better Crops* is a practical guide to ecological soil management that provides background information as well as details of soil-improving practices. This book is meant to give the reader a holistic appreciation of the importance of soil health and to suggest ecologically sound practices that help to develop and maintain healthy soils.

Building Soils for Better Crops has evolved over time. The first edition focused exclusively on the management of soil organic matter. It is *the* central component of healthy soils, and if you follow practices that build and maintain good levels of soil organic matter, you will find it easier to grow healthy and high-yielding crops. Plants can better withstand droughty conditions and won't be as bothered by insects and diseases. By maintaining adequate levels of organic matter in soil, you have less reason to use as much commercial fertilizer, lime and pesticides as many farmers now purchase. Soil organic matter is that important. The second edition expanded the scope to other aspects of soil management and became recognized as a highly influential book that inspired many towards holistic soil health management.

The third edition was rewritten, expanded with new chapters, and had broader geographical scope; it evolved into a more comprehensive treatise of sustainable soil management for a global audience. Since its publication in 2009, the understanding and promotion of soil health and more holistic approaches to managing crops and soils has truly taken off. We now have numerous major soil health initiatives by governments and NGOs in the United States and around the world.

The fourth edition provides critical updates to reflect the new science and many new exciting developments in soil health. It still has a primary perspective on farming and soils in the United States, but we further expanded the global scope and included a new chapter on growing plants in urban environments.

A book like this one cannot give exact answers to problems on specific farms. In fact, we purposely stay away from prescriptive approaches. There are just too many differences from one field to another, one farm to another, and one region to another, to warrant blanket recommendations. To make specific suggestions, it is necessary to know the details of the soil, crop, climate, machinery, human considerations and other variable factors. Good soil management is knowledge intensive and needs to be adaptive. It is better achieved through education and understanding than with simple recommendations.

Over many millennia, people have struggled with the same issues of maintaining soil productivity as we struggle with today. We quote some of these people in many of the epigraphs at the beginning of each chapter in appreciation for those who have come before. *Vermont Agricultural Experiment Station Bulletin No. 135,* published in 1908, is especially fascinating; it contains an article by three scientists about the importance of soil organic matter that is strikingly modern in many ways. The message of Edward Faulkner's *Plowman's Folly*—that reduced tillage and increased use of organic residues are essential to improving soil—is as valid today as it was in 1943 when it was first published. And let's not forget the first textbook of soil management, Jethro Tull's *A Horse-Hoeing Husbandry, or an Essay on the Principles of Tillage and Vegetation,* first published in 1731. Although it discusses now-refuted concepts, like the need for intensive tillage, it also contains the blueprints for modern seed drills and crop rotations. The saying is right: what goes around comes around. Sources are cited at the end of each chapter and at the end of the book, although what's provided is not a comprehensive list of references on the subject.

Many people reviewed individual chapters for this edition or the entire manuscript at one stage or another and made very useful suggestions. We would like to thank Anthony Bly, Tom Bruulsema, Dennis Chessman, Doug Collins, Willie Durham, Alan Franzluebbers, Julia Gaskin, Vern Grubinger, Joel Gruver, Ganga Hettiarachchi, Jim Hoorman, Tom Jensen, Zahangir Kabir, Doug Karlen, Carl Koch, Peter Kyveryga, Doug Landblom, Matt Leibman, Kate MacFarland, Teresa Matteson, Tai McClellan Maaz, Justin Morris, Rob Myers, Doug Peterson, Heidi Peterson, Sarah Pethybridge, Steve Phillips, Matt Ryan, Paul Salon, Brandon Smith, John Spargo, Diane Stott, Candy Thomas, Sharon Weyers, Charlie White and Marlon Winger.

We recognize colleagues who provided photos in the figure captions, and we are grateful for their contributions. All other photos are our own or are in the public domain. We also acknowledge some of our colleagues—Bob Schindelbeck, Joseph Amsili, Jean Bonhotal, George Abawi, David Wolfe, Omololu (John) Idowu, Bianca and Dan Moebius-Clune, Ray Weil, Nina Bassuk, and Rich Bartlett (deceased)—as well as many of our former students and postdocs, who have made contributions or whose ideas, insights and research have helped shape our understanding of the subject. And we thank our wives, Amy Demarest and Cindy van Es, for their patience and encouragement during the writing of this book. Any mistakes are, of course, ours alone.

A final note about units of measure. Agricultural practitioners are notorious for using different units around the world, like bushels, quintals, hectares, acres, manzanas, and imperial or metric tons. This book has an expanding global audience, and many readers outside North America, and scientists like us, would perhaps prefer the use of metric units. But we decided to maintain the use of imperial units in the book for the convenience of our original target audience. We trust that it does not excessively distract from your reading experience and that readers will make the conversions when the numbers really matter.

Fred Magdoff, University of Vermont
Harold van Es, Cornell University

January 2021

INTRODUCTION

... it is our work with living soil that provides sustainable alternatives to the triple crises of climate, energy, and food. No matter how many songs on your [smartphone], cars in your garage, or books on your shelf, it is plants' ability to capture solar energy that is at the root of it all. Without fertile soil, what is life?

—VANDANA SHIVA, 2008

Throughout history, humans have worked the fields, and land degradation has been a common occurrence. Many civilizations have disintegrated from unsustainable land use, including the cultures of the Fertile Crescent in the Middle East, where the agricultural revolution first began about 10,000 years ago. The 2015 *Status of the World's Soil Resources* report produced by FAO's Intergovernmental Technical Panel on Soils raised global awareness on soil's fundamental role for life on earth but estimated that 33 percent of land is moderately to highly degraded, and it is getting worse. The report identified 10 main threats to soil's ability to function: soil erosion, soil organic matter loss, nutrient imbalance, soil acidification, soil contamination, waterlogging, soil compaction, soil sealing, salinization and loss of soil biodiversity. The current trajectories have potentially catastrophic consequences and millions of people are at risk, especially in some of the most vulnerable regions. Moreover, this has become much more relevant as soils are critical environmental buffers in a world that sees its climate rapidly changing.

In the past, humankind survived because people developed new lands for growing food. But a few decades ago the total amount of agricultural land actually began to decline because new land could no longer compensate for the loss of old land retired from agriculture due to degradation or due to its use for urban, suburban and commercial development. The loss of agricultural land combined with three current trends—increasing populations; greater consumption of animal products produced in large-scale facilities, which creates less-efficient use of crop nutrients; and expanding acreages for biofuel crops—strains our ability to produce sufficient food for the people of the world. We have now reached a point where we are expanding into marginal lands like shallow hillsides and arid areas, which are very fragile and can degrade rapidly (Figure I.1). Another area of agricultural expansion is virgin savannah and tropical rainforest, which are the last remnants of unspoiled and biologically rich land and help moderate climate change. The rate of deforestation at this time is very disconcerting: if continued at this level, there will be little virgin forest left by the middle of the century. We must face the reality that we are running

Figure I.1. Reaching the limits: Marginal rocky land is put into production in Africa.

out of land and need to use the agricultural land we have more productively. We have already seen hunger and civil strife over limited land resources and productivity, and global food crises are a regular occurrence. Some countries with limited water or arable land are purchasing or leasing land in other countries to produce food for the "home" market, and investors are obtaining land in Africa, Southeast Asia and Latin America.

Nevertheless, human ingenuity has helped us overcome many agricultural challenges, and one of the truly modern miracles is our agricultural system, which produces abundant food. High yields often come from the use of improved crop varieties, fertilizers, pest control products and irrigation. These yields have resulted in food security for much of the developed world. At the same time, mechanization and the ever-improving capacity of field equipment allow farmers to work an increasing amount of acreage. But we have also spectacularly altered the flows of organic matter and nutrients in an era when agricultural commodities are shipped across continents and oceans. Despite the high productivity per acre and per person, many farmers, agricultural scientists and Extension specialists see severe problems associated with our intensive agricultural production systems. Examples abound:

- With conventional agricultural practices heavily dependent on fossil fuels, unpredictable swings in their prices affect farmers' net income.
- Prices farmers receive and food prices in retail stores fluctuate in response to both supply and demand, as well as to speculation in the futures markets.
- Increasing specialization of agriculture and geographical separation of grain and livestock production areas—even the diversion of food and animal feed crops to ethanol and biodiesel production—have reduced the natural cycling of carbon and nutrients with severe consequences for soil health and water and air quality.
- Too much nitrogen fertilizer or animal manure often causes elevated nitrate concentrations in streams and groundwater. These concentrations can become high enough to pose a human health hazard. Many of the biologically rich estuaries and where rivers flow into seas around the world—the Gulf of Mexico, Baltic Sea and increasingly other areas—are hypoxic (have low oxygen levels) during late summer months due to nitrogen enrichment from agricultural sources.
- Phosphate and nitrate in runoff and drainage water enter freshwater bodies and degrade their quality by stimulating algae growth.
- Antibiotics used to fight diseases in confined, concentrated farm animals, or used just to promote growth, can enter the food chain and may be found in the meat we eat. Perhaps even more important: their overuse on farms where large numbers of animals are crowded together has resulted in outbreaks of human illness from strains of disease-causing bacteria that have become resistant to many antibiotics.
- Erosion associated with conventional tillage and lack of good rotations degrades our precious soil and, at the same time, causes reservoirs, ponds and lakes to silt up.
- Soil compaction by large equipment reduces water infiltration and increases runoff, thereby increasing flooding while at the same time making soils more drought prone.
- Agriculture, as it expanded into desert regions, has become by far the largest consumer of fresh water. In many parts of the world groundwater is being used for agriculture faster than nature can replenish it. This is a global phenomenon, with over half of the largest aquifers and rivers in the world being exploited at rates exceeding recharge.

The whole modern system of agriculture and food is based on extensive fossil fuel use: to make and power large field equipment, produce fertilizers and pesticides, dry grains, process food products, and transport them over long distances. With the declining production from easily extractable oil and gas, there has been a greater dependence on sources that are more difficult to extract, such as deep wells in the oceans, the tar sands of Canada and a number of shale deposits (accessed by hydraulic fracturing of the rock). All of these sources have significant negative effects on soil, water, air and climate. With the price of crude oil fluctuating but tending to be much greater than in the 20th century, and with the current relatively low price of natural gas dependent on a polluting industry (water pollution and methane emissions with hydraulic fracturing), the economics of the "modern" agricultural system need to be reevaluated.

The food we eat and our surface and groundwaters are sometimes contaminated with disease-causing organisms and chemicals used in agriculture. Pesticides used to control insects, weeds and plant diseases can be found in foods, animal feeds, groundwater and surface water running off agricultural fields. Farmers and farmworkers are at special risk. Studies have shown higher cancer rates among those who work with or near certain pesticides. Children in areas where pesticides are used extensively are also at risk of having developmental problems. When considered together, the costs from these inadvertent byproducts of agriculture are huge. More than a decade ago, the negative effects on wildlife, natural resources, human health and biodiversity in the United States were estimated to cost between $6 billion and $17 billion per year. The general public is increasingly demanding safe, high-quality food that is produced without excessive damage to the environment—and many are willing to pay a premium to obtain it.

To add to the problems, farmers are in a perpetual struggle to maintain a decent standard of living. The farmer's bargaining position has weakened as corporate consolidations and other changes occur with the agricultural input (seeds, fertilizers, pesticides, equipment, etc.), food processing and marketing sectors. For many years the high cost of purchased inputs and the low prices of many agricultural commodities, such as wheat, corn, cotton and milk, caught farmers in a cost-price squeeze that made it hard to run a profitable farm. As some farms go out of business, this dynamic has favored the expansion of production among remaining farmers seeking physical and economic advantages of scale.

Given these problems, you might wonder if we should continue to farm in the same way. A major effort is under way by farmers, Extension educators and researchers to develop and implement practices that are both more environmentally sound than conventional practices and, at the same time, more economically rewarding for farmers. As farmers use management skills and better knowledge to work more closely with the biological world and with the consumer, they frequently find that there are ways to increase profitability by decreasing the use of inputs purchased off the farm and by selling directly to the end user.

Governments have played an ambiguous role in promoting sustainability in agriculture. Many promoted certain types of farming and production practices that worsened the problems, for example through fertilizer subsidies, crop insurance schemes and price guarantees. But governments also pour funds into conservation programs (especially in the United States), require good farming practices for receiving subsidies (especially Europe) and establish farming standards (e.g., for organic production and for fertilizer and pesticide use). A new bright spot is that private-sector sustainability initiatives in agriculture are gaining ground. The general public is increasingly aware of the aforementioned issues and is demanding change. Several large consumer-facing retail and food companies (many that are international) therefore see a benefit from projecting an image of corporate sustainability. They are using supply chain management approaches to work with agricultural businesses and farmers to promote environmentally compatible farming. Indeed, the entire agriculture and food sector benefits when it becomes more sustainable, and there are numerous win-win opportunities to reduce waste and inefficiencies while helping farmers become more profitable over the long run.

SOIL HEALTH INTEGRAL TO SUSTAINABLE AGRICULTURE

You might wonder how soil health fits into all this. It turns out that it is a key aspect of agricultural sustainability because soils are foundational to the food production system while also providing other critical services related to water, air and climate. With the new emphasis on sustainable agriculture comes a reawakening of interest in soil health. Early scientists, farmers and gardeners were well aware of the importance of soil quality and organic matter to the productivity of soil after they saw fertile lands become unproductive. The significance of soil organic matter, including living organisms in the soil, was understood by scientists at least as far back as the 17th century. John Evelyn, writing in England during the 1670s, described the importance of topsoil and explained that the productivity of soils tended to be lost with time. He noted that their fertility could be maintained by adding organic residues. Charles Darwin, the great natural scientist of the 19th century who developed the modern theory of evolution, studied and wrote about the importance of earthworms to nutrient cycling and the general fertility of the soil.

Around the turn of the 20th century, there was again an appreciation of the importance of soil health. Scientists realized that "worn-out" soils, whose productivity had drastically declined, resulted mainly from the depletion of soil organic matter. At the same time, they could see a transformation coming: Although organic matter was "once extolled as the essential soil ingredient, the bright particular star in the firmament of the plant grower, it fell like Lucifer" under the weight of "modern" agricultural ideas (Hills, Jones, and Cutler, 1908). With the availability of inexpensive fertilizers and larger farm equipment after World War II, and with the availability of cheap water for irrigation in dry regions, many people forgot or ignored the importance of organic matter in promoting high-quality soils. In fact, the trading of agricultural commodities in a global economy created a serious imbalance, with some production regions experiencing severe organic matter losses while others had too much. For example, in specialized grain production, most of the organic matter and nutrients—basic ingredients for soil health—are harvested and routinely shipped off the farm to feed livestock or to be industrially processed many miles away, sometimes across continents or oceans. They are never returned to the same production fields, and moreover the carbon and nutrients pose problems at their destinations because the soils became overloaded.

As farmers and scientists were placing less emphasis on soil organic matter during the last half of the 20th century, farm machinery was also getting larger. More horsepower for tractors allowed more land to be worked by fewer people. Large four-wheel-drive tractors allowed farmers to do field work when the soil was wet, creating severe compaction and sometimes leaving the soil in a cloddy condition, requiring more harrowing than otherwise would be needed. The moldboard plow was regarded as a beneficial tool in 19th and early 20th century agriculture that helped break virgin sod and controlled perennial weeds, but with repeated use it became a source of soil degradation by breaking down soil structure and leaving no residues on the surface. Soils were left bare and very susceptible to wind and water erosion. As farm sizes increased, farmers needed heavier manure and fertilizer spreaders as well as more passes through the field to prepare a seedbed, plant,

> *"[Organic matter was] once extolled as the essential soil ingredient, the bright particular star in the firmament of the plant grower. …"*

spray pesticides and harvest, both of which created more soil compaction.

A new logic developed that most soil-related problems could be dealt with by increasing external inputs. This is a reactive way of dealing with soil issues—you respond after seeing a "problem" in the field. If a soil is deficient in some nutrient, you buy fertilizer and spread it on the soil. If a soil doesn't store enough rainfall, all you need is irrigation. If a soil becomes too compacted and water or roots can't easily penetrate, you use a big implement to tear it open. If a plant disease or insect infestation occurs, you apply a pesticide. But are these really individual and unrelated problems? Perhaps they are better viewed as symptoms of a deeper, underlying problem. The ability to tell the difference between what is the underlying problem and what is only a symptom of a problem is essential to deciding on the best course of action. For example, if you are hitting your head against a wall and you get a headache, is the problem the headache and is aspirin the best remedy? Clearly, the real problem is your behavior, not the headache, and the best solution is to stop banging your head against the wall!

What many people think are individual problems may just be symptoms of a degraded, poor-quality soil, which in turn is often related to the general way it is farmed. These symptoms are usually directly related to soil organic matter depletion, lack of a thriving and diverse population of soil organisms, chemical pollution or compaction caused by heavy field equipment. Farmers have been encouraged to react to individual symptoms instead of focusing their attention on general soil health management. A different approach—agroecology—is gaining wider acceptance, implementing farming practices that take advantage of the inherent strengths of natural systems and aiming to create healthy soils. In this way, farmers prevent many symptoms of unhealthy soils from developing, instead of reacting after they develop and trying to overcome them through expensive inputs. If we are to work together with nature rather than attempt to overwhelm and dominate it, then building and maintaining good levels of organic matter in our soils are as critical as managing physical conditions, pH and nutrient levels. Interestingly, the public's concern about climate change has generated a renewed interest in soil organic matter management through so-called carbon farming. Indeed, putting more carbon into the soil can also help reduce global warming.

What many people think are individual problems may just be symptoms of a degraded, poor-quality soil.

The use of inputs such as fertilizers, pesticides and fuels—aided by their relatively low cost—was needed for agricultural development and for feeding a rapidly expanding global population. Let's not ignore that. But it overlooked the important role of soil health and helped push the food production system towards practices where environmental consequences and long-term impacts are not internalized into the economic equation. It could then be argued that matters will not improve unless these structural problems are recognized and economic incentives are changed. Many farming regions have become economically dependent on a global system of export and import of commodities that are not compatible with long-term soil health management. Also, the sector that sells farm machinery and inputs has become highly consolidated and powerful, and these corporations generally have an interest in maintaining the status quo. Input prices have increased markedly over the last decades while prices for those commodities, with the exception of short-term price spikes, have tended to remain low. It is believed that this drives farming towards greater efficiencies, but not necessarily in a sustainable manner. In this context, we argue that sustainable soil management is profitable, and that such management will cause profitability to increase with greater scarcity of resources and higher prices of crop inputs. Even the interests of corporations in the agricultural and food industries can be served in this paradigm.

This book has four parts. Part 1 provides background information about soil health and organic matter: what it is, why it is so important, why we have problems, the importance of soil organisms, and why some soils are of higher quality than others. Part 2 includes discussions of soil physical properties, soil water storage, and carbon and nutrient cycles and flows. Part 3 deals with the ecological principles behind, and the practices that promote, building healthy soil. It begins with chapters that place a lot of emphasis on promoting organic matter buildup and maintenance. Following practices that build and maintain organic matter may be the key to soil fertility and may help solve many problems. Practices for enhancing soil quality include the use of animal manures and cover crops; good residue management; appropriate selection of rotation crops; use of composts; reduced tillage; minimizing soil compaction and enhancing aeration; better nutrient and amendment management; good irrigation and drainage; and adopting specific conservation practices for erosion control. Part 4 discusses how you can evaluate soil health and combine soil-building management strategies that actually work on the farm, and how to tell whether the health of your soils is improving.

SOURCES

Hills, J.L., C.H. Jones and C. Cutler. 1908. Soil deterioration and soil humus. In *Vermont Agricultural Experiment Station Bulletin 135*. pp. 142–177. University of Vermont, College of Agriculture: Burlington, VT.

Magdoff, F. 2013. Twenty-First-Century Land Grabs: Accumulation by Agricultural Dispossession. *Monthly Review* 65(6): 1–18.

Montgomery, D. 2007. *Dirt: The Erosion of Civilizations*. University of California Press: Berkeley, CA.

Montanarella, L., et al. 2016. World's soils are under threat. *Soil* (2): 79–82.

Tegtmeier, E.M. and M.D. Duffy. 2004. External costs of agricultural production in the United States. *International Journal of Agricultural Sustainability* 2: 1–20.

FAO and ITPS. 2015. Status of the World's Soil Resources (SWSR)—Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

PART 1

ORGANIC MATTER—THE KEY TO HEALTHY SOILS

Photo by Dennis Nolan

Chapter 1

HEALTHY SOILS

> *All over the country [some soils are] worn out, depleted, exhausted, almost dead. But here is comfort: These soils possess possibilities and may be restored to high productive power, provided you do a few simple things.*
>
> —C.W. BURKETT, 1907

It should come as no surprise that many cultures have considered soil central to their lives. After all, people were aware that the food they ate grew from the soil. Our ancestors who first practiced agriculture must have been amazed to see life reborn each year when seeds placed in the ground germinated and then grew to maturity. In the Hebrew Bible, the name given to the first man, Adam, is the masculine version of the word "earth" or "soil" (*adama*). The name for the first woman, Eve (or Hava in Hebrew), comes from the word for "living." Soil and human life were considered to be intertwined. A particular reverence for the soil has been an important part of the cultures of many civilizations, including Native American tribes. In reality, soil *is* the basis of all terrestrial life. We humans are derived from soil. Aside from when we eat fish and other aquatic organisms, we obtain the essential elements in our bodies, such as the calcium and phosphorus in our bones and teeth, the nitrogen in our proteins, the iron in our red blood cells, and so on, all by directly or indirectly consuming plants that took these from the soil.

Although we focus on the critical role soils play in growing crops, it's important to keep in mind that soils also provide other important services. Soils govern whether rainfall runs off the field or enters the ground and eventually helps recharge underground aquifers. When a soil is stripped of vegetation and starts to degrade, excessive runoff and flooding are more common. Soils also absorb, release and transform many different chemical compounds. For example, they help to purify wastes flowing from the septic system drain fields in your backyard. Soils also provide habitats for a diverse group of organisms, many of which are very important, such as those bacteria that produce antibiotics and fungi that help plants obtain nutrients and water and improve soil structure. Soil organic matter stores a huge amount of atmospheric carbon. Carbon, in the form of carbon dioxide, is a greenhouse gas associated

Photo by Dan Anderson

with global warming. So, by increasing soil organic matter, more carbon can be stored in soils, reducing the potential for climate change. We also use soils as a foundation for roads, industry and our communities.

HOW IS SOIL MADE?

Before we consider what makes a soil rich or poor, we should learn how it comes into existence. Soil consists of four parts: solid mineral particles, water, air and organic matter. The particles are generally of sand, silt and clay size (and sometimes also larger fragments) and were derived from weathering of rocks or deposition of sediments. They mainly consist of silicon, oxygen, aluminum, potassium, calcium, magnesium, phosphorus, potassium and other minor chemical elements. But these elements are generally locked up in the crystalline particles and are not directly available to plants. However, unlike solid rock, soil particles have pore spaces in between them that allow them to hold water through *capillary action*: the soil can act like a sponge. This is an important process because it allows the soil water, with the help of carbon dioxide in the air, to very slowly dissolve the mineral particles and release nutrients—we call this *chemical weathering*. The soil water and dissolved nutrients, together referred to as the *soil solution*, are now available for plants. The air in the soil, which is in contact with the air above ground, provides roots with oxygen and helps remove excess carbon dioxide from respiring root cells.

What role do plants and soil organisms play? They facilitate the cycling of organic matter and of the nutrients, which allows soil to continue supporting life. Plants' leaves capture solar energy and atmospheric carbon from carbon dioxide (CO_2) through photosynthesis. The plant uses this carbon to build the sugars, starches and all the other organic chemicals it needs to live and reproduce. At the same time, plant roots absorb both soil water and the dissolved nutrients (nitrogen is added to soils or directly to plants through associated biological processes). Now, the mineral nutrients that were derived from the soil are stored in the plant biomass *in organic form* in combination with the carbon from the atmosphere. The seeds tend to be especially high in nutrients, but the stems and leaves also contain important elements. Eventually plants die and their leaves and stems return to the soil surface. Sometimes plants don't return directly to the soil surface, but rather are eaten by animals. These animals extract nutrients and energy for themselves and then defecate what remains. Soil organisms help to incorporate both manure and plant residues into the soil, while the roots that die, of course, are already in the soil. This dead plant material and manure become a feast for a wide variety of organisms—beetles, spiders, worms, fungi, bacteria, etc.—that in turn benefit from the energy and nutrients the plants had previously stored in their biomass. At the same time, the decomposition of organic material makes nutrients available again to plants, now completing the cycle.

But is it a perfect cycle? Not quite, because it has not evolved to function under intensive agricultural production. The chemical weathering process that adds new nutrients into the cycle continues at a very slow pace. On the other end of the cycle the soil captures some of the organic matter and puts it "in storage." This happens because soil mineral particles, especially clays, form bonds with the organic molecules and thereby protect them from further decomposition by soil organisms. In addition, organic matter particles inside soil aggregates are protected from decomposition. Over a long time, the soil builds up a considerable reservoir of nutrients from slowly decomposing minerals and carbon, and of energy from plant residue in the form of organic matter—similar to putting a small amount of money into a retirement account each month. This organic matter storage system is especially impressive with prairie and steppe soils in temperate regions (places like the central United States, Argentina and Ukraine) because natural grasslands have deep roots and high organic matter turnover (Figure 1.1).

In a natural system this process is quite efficient and has little nutrient leakage. It maximizes the use of mineral nutrients and solar energy until the soil has reached its maximum capacity to store organic matter (more about this in Chapter 3). But when lands were first developed for agriculture, plowing was used to suppress weeds and to prepare the soil for planting grain crops. Plowing was also beneficial because it accelerated organic matter decomposition and released more nutrients than unplowed land. This was a major rift in organic matter cycling, because it caused more organic matter to be lost each year than was returned to the soil. In addition, a related rift occurred in nutrient cycling as some of the nutrients were harvested as part of the crop, removed from the fields and never returned. Other nutrients were washed out of the soil. Over time, the organic matter bank account that had slowly built up under natural vegetation was being drawn down.

However, until organic matter became seriously depleted, its increased decomposition through tillage helped to supply crops with released nutrients and these rifts did not cause widespread concern. On sloping lands these losses went much faster because the organic matter near the surface also eroded away after the soil was exposed to rain and wind. Only in the past century did we find effective ways to replenish the lost nutrients by applying fertilizers that are derived from geologic deposits or the Haber-Bosch process for producing nitrogen fertilizers. But the need to replace the organic matter (carbon) was mostly ignored until recently.

The organic matter in the soil is more complex and plays many important roles in soils that we will discuss in Chapter 2. Not only does it store and supply nutrients and energy for organisms, it also helps form aggregates when mineral and organic particles clump together. When it is made up of large amounts of different-sized aggregates, the soil contains more spaces for storing water and allowing gas exchange, as oxygen enters for use by plant roots and by soil organisms and the carbon dioxide produced by organisms leaves the soil. So in summary, the mineral particles and pore spaces form the basic structure of the soil, but the organic matter is mostly what makes it *fertile*.

Figure 1.1. Soils build a storage reservoir of carbon and nutrients in organic matter, and can also hold water and air. The organic matter builds up from decayed plant material and accumulates mostly in the dark root zone under the surface. Photo by USDA-NRCS.

WHAT KIND OF SOIL DO YOU WANT?

Farmers sometimes use the term *soil health* to describe the condition of the soil. Scientists usually use the term *soil quality*, but both refer to the same idea: how well the soil is functioning for whatever use is being considered. The concept of *soil health* focuses on the human factor—the *anthropogenic* influence—that is increasingly significant due to many years of intensive management. This is different from the inherent differences in soils that are the result of the natural factors that formed the soil, such as the parent material, climate, etc. Thereby, an analogy with humans is apt: We may have some natural differences from our genetic backgrounds (taller or shorter, fairer or darker, etc.), but our health still strongly affects the way we can function and is greatly influenced by how we treat our bodies.

In agriculture, soil health becomes a question of how good the soil is at supporting the growth of high-yielding, high-quality and healthy crops. Given this, how then would you know a high-quality soil from a lower-quality soil? Most farmers and gardeners would say they know one when they see one. Farmers can certainly tell you which of the soils on their farms are of low, medium or high quality, and oftentimes they refer to how dark and crumbly it is. They know high-quality soil because it generates higher yields with less effort. Less rainwater runs off and fewer signs of erosion are seen on the better-quality soils. Less power is needed to operate machinery on a healthy soil than on poor, compacted soils. But there are other characteristics that we'd like a soil to have. These can be condensed into seven desirable attributes of healthy soils:

1. **Fertility**. A soil should have a sufficient supply of nutrients throughout the growing season.
2. **Structure**. We want a soil with good tilth so that plant roots can fully develop with the least amount of effort. A soil with good tilth is more spongy and less compact than one with poor tilth. A soil that has a favorable and stable soil structure also promotes rainfall infiltration and water storage for plants to use later.
3. **Depth**. For good root growth and drainage, we want a soil with sufficient depth before a compact soil layer or bedrock is reached.
4. **Drainage and aeration**. We want a soil to be well drained so that it dries enough in the spring and during the following rains to permit timely field operations. Also, it's essential that oxygen is able to enter the root zone and just as important that carbon dioxide leaves it (it also enriches the air near the leaves as it diffuses out of the soil, allowing plants to have higher rates of photosynthesis). Keep in mind that these general characteristics do not necessarily hold for all crops. For example, flooded soils are desirable for cranberry and paddy rice production.
5. **Minimal pests**. A soil should have low populations of plant disease and parasitic organisms. Certainly, there should also be low weed pressure, especially of aggressive and hard-to-control weeds. Most soil organisms are beneficial, and we certainly want high amounts of organisms that help plant growth, such

THINK LIKE A ROOT!

If you were a root, what would you like from an ideal soil? Surely you'd want the soil to provide adequate nutrients and to be porous with good tilth, so that you could easily grow and explore the soil and so that the soil could store large quantities of water for you to use when needed. But you'd also like a very biologically active soil, with many beneficial organisms nearby to provide you with nutrients and growth-promoting chemicals, as well as to keep potential disease organism populations as low as possible. You would not want the soil to have any chemicals, such as soluble aluminum or heavy metals, that might harm you; therefore, you'd like the pH to be in a proper range for you to grow, and you wouldn't want to be in a soil that somehow became contaminated with toxic chemicals. You would also not want any subsurface layers that would restrict your growth deep into the soil.

as earthworms and many bacteria and fungi.

6. **Free of toxins**. We want a soil that is free of chemicals that might harm the plant. These can occur naturally, such as soluble aluminum in very acid soils or excess salts and sodium in arid soils. Potentially harmful chemicals also are introduced by human activity, such as fuel oil spills or when sewage sludge with high concentrations of toxic elements is applied.
7. **Resilience**. Finally, a high-quality soil should resist being degraded. It should also be resilient, recovering quickly after unfavorable changes like compaction.

THE NATURE AND NURTURE OF SOILS

Some soils are exceptionally good for growing crops and others are inherently unsuitable, but most are in between. Many soils also have limitations, such as low organic matter content, texture extremes (coarse sand or heavy clay), poor drainage or layers that restrict root growth. Midwestern loess-derived prairie soils are naturally blessed with a combination of a silt loam texture and high organic matter content. By every standard for assessing soil health, these soils, in their virgin state, would rate very high. But even many of these prairie soils required drainage in order for them to be highly productive.

The way we care for, or *nurture*, a soil modifies its inherent nature. A good soil can be abused through years of poor management and can turn into one with poor health, although it generally takes a lot of mistreat ment to reach that point. On the other hand, an innately challenging soil may be very "unforgiving" of poor management and quickly become even worse. For example, a heavy clay loam soil can be easily compacted and turned into a dense mass. Naturally good and poor soils will probably never reach parity through good farming practices because some limitations simply cannot be completely overcome, but both can be productive if they are managed well.

HOW DO SOILS BECOME DEGRADED?

Although we want to emphasize healthy, high-quality soils because of their ability to produce high yields of crops, it is also crucial to recognize that many soils in the United States and around the world have become degraded: they have become "worn out." Degradation most commonly begins with tillage—plowing and harrowing the soil—causing soil aggregates to break apart, which then causes more rapid loss of soil organic matter as organisms have greater access to residues. This accelerates erosion, because soils with lower organic matter content and less aggregation are more prone to accelerated erosion. And erosion, which takes away topsoil enriched with organic matter, initiates a downward spiral resulting in poor crop production. Soils become compact, making it hard for water to infiltrate and for roots to develop properly. Erosion continues and nutrients decline to levels too low for good crop growth. The development of saline (too salty) soils under irrigation in arid regions is another cause of reduced soil health. (Salts added in the irrigation water need to be leached beneath the root zone to avoid the problem.)

Soil degradation caused significant harm to many early civilizations, including the drastic loss of productivity resulting from soil erosion in many locations in the Middle East (such as present day Israel, Jordan, Iraq and Lebanon) and southern Europe. This led either to colonial ventures to help feed the citizenry—like the Romans invading the Egyptian breadbasket—or to the decline of the civilization. The only exceptions were the convergence zones in the landscapes, valleys and deltas where the nutrients and sediments flow together and fertility can be maintained for many centuries (more about this in Chapter 7).

Tropical rainforest conditions (high temperature and rainfall, with most of the organic matter near the soil surface) may lead to significant soil degradation within two or three years of conversion to cropland. This is the reason the "slash and burn" system, with

Figure 1.2. Agricultural soil (left) and natural soil (grassland; right) from adjacent sites in the U.S. Great Plains. Agricultural soil has lower soil organic matter and higher density. Photos by Kirsten Kurtz.

people moving to a new patch of forest every few years, developed in the tropics. After farmers depleted the soils (the readily decomposed organic matter) in a field, they would cut down and burn the trees in the new patch, allowing the forest and soil to regenerate in previously cropped areas.

The westward push of U.S. agriculture was stimulated by rapid soil degradation in the East, originally a zone of temperate forest. Under the environmental conditions of the Great Plains (moderate rainfall and temperature, with organic matter distributed deeper in the soil), it took many decades for the effects of soil degradation to become evident (Figure 1.2).

The extent of deteriorating soil on a worldwide basis is staggering: Soil degradation has progressed so far as to decrease yields on about 20% of all the world's cropland and on 19–27% of the grasslands and rangelands. The majority of agricultural soils are in only fair, poor or very poor condition. Erosion remains a major global problem, robbing people of food and each year continuing to reduce the productivity of the land. Each year some 30–40 billion tons of topsoil are eroded from the croplands of the world.

HOW DO YOU BUILD A HEALTHY, HIGH-QUALITY SOIL?

Some characteristics of healthy soils are relatively easy to achieve. For example, an application of ground limestone will make a soil less acid and will increase the availability of many nutrients to plants. But what if the soil is only a few inches deep? In that case, there is little that can be done within economic reason, except on a very small, garden-size plot. If the soil is poorly drained because of a restricting subsoil layer of clay, tile drainage can be installed, but at a significant cost economically and environmentally.

We use the term *building soils* to emphasize that the nurturing process of converting a degraded or low-quality soil into a truly high-quality one requires understanding, thought and significant actions. It is a process that mirrors the building of soil through natural processes where plants and organic matter are key elements. This is also true for maintaining or

> … What now remains of the formerly rich land is like the skeleton of a sick man, with all the fat and soft earth having wasted away and only the bare framework remaining. Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only food for bees. Once the land was enriched by yearly rains, which were not lost, as they are now, by flowing from the bare land into the sea. The soil was deep, it absorbed and kept the water in the loamy soil, and the water that soaked into the hills fed springs and running streams everywhere. Now the abandoned shrines at spots where formerly there were springs attest that our description of the land is true.
>
> —PLATO, 4TH CENTURY B.C.

EVALUATING YOUR SOILS

Score cards and laboratory tests have been developed to help farmers assess their soils, using scales to rate the health of soils. In the field, you can evaluate the presence of earthworms, severity of erosion, ease of tillage, soil structure and color, extent of compaction, water infiltration rate and drainage status. Doing some digging can be especially enlightening! Then you rate crops growing on the soils by such characteristics as their general appearance, growth rates, root health, degree of resistance to drought and yield. It's a good idea for all farmers to fill out such a scorecard for every major field or soil type on your farm every few years, or, alternatively, to send in soil to a lab that offers soil health analyses. But even without doing that, you probably already know what a really high-quality and healthy soil—one that would consistently produce good yields of high-quality crops with minimal negative environmental impact—would be like. You can read more on evaluating soil health in Chapter 23.

improving already healthy soils. Soil organic matter has a positive influence on almost all of the characteristics we've just discussed. As we will see in chapters 2 and 8, soil organic matter is even critical for managing pests. Appropriate organic matter management is, therefore, the foundation for high-quality soil and for a more sustainable and thriving agriculture. It is for this reason that so much space is devoted to organic matter in this book. However, we cannot forget other critical aspects of management, such as trying to lessen soil compaction and good nutrient management.

Although the details of how best to create high-quality soils differ from farm to farm and even field to field, the general approaches are the same. For example:

- **Minimize tillage** and other soil disturbances to maintain soil structure and decrease losses of native soil organic matter.
- **Implement a number of practices** that add diverse sources of organic materials to the soil.
- **Maximize live roots** in the soil and use **rotations and cover crops** that include a diverse mix of crops with different types of root systems.
- **Provide plenty of soil cover** through cover crops and/or surface residue even when economic crops aren't present in order to protect the soil from raindrops and temperature extremes.
- Whenever traveling on the soil with field equipment, use practices that help **develop and maintain good soil structure**.
- Manage **soil fertility** status to maintain optimal pH levels for your crops and a sufficient supply of nutrients for plants without contributing to water pollution.
- In arid regions, reduce the amount of **sodium or salt** in the soil.

There are also large-scale considerations related to the structure of agriculture and associated nutrient and carbon flows that tie into this. Later in the book we will return to these and other practices for developing and maintaining healthy soils.

SOIL HEALTH, PLANT HEALTH AND HUMAN HEALTH

Of the literally tens of thousands of species of soil organism, relatively few cause plant diseases. And the same is true for human diseases, with examples such as tetanus (a toxin produced by a bacterium), hookworm (a nematode), and ringworm (a fungus). But the physical condition of soil can also affect human health. For example, people in the path of dust storms, which pick up fine particles from bare soils, may have significant