THIRD EDITION

BUILDING SOILS FOR BETTER CROPS

SUSTAINABLE SOIL MANAGEMENT

BY FRED MAGDOFF AND HAROLD VAN ES

SARE
Sustainable Agriculture Research & Education
HANDBOOK 10

BUILDING SOILS FOR BETTER CROPS

SUSTAINABLE SOIL MANAGEMENT

THIRD EDITION

BY FRED MAGDOFF AND HAROLD VAN ES

HANDBOOK SERIES BOOK 10

Published in 2009 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 the Sustainable Agriculture Research and Education (SARE) program under cooperative agreements with USDA's National Institute of Food and Agriculture, University of Maryland and University of Vermont.

To order:
Online: Visit www.sare.org/WebStore
By check or purchase order: Make payable to Sustainable Agriculture Publications and send to:

SARE Outreach Publications
P.O. Box 753
Waldorf, MD 20604-0753

Cost:
- $20.95 for orders of 1-9 books
- $15.71 for 10-24 books (a 25% discount)
- $10.47 for 25 or more books (a 50% discount)

Shipping:
- $5.95 for first book (within USA). Add $2 s/h for each additional book—up to nine books—shipped within USA.
- For s/h on orders of 10 or more books, call (301) 374-9696 or visit www.sare.org/WebStore.

International or credit card orders:
- Call (301) 374-9696 or visit www.sare.org/webstore.

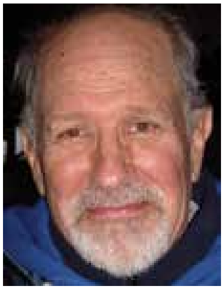
Library of Congress Cataloging-in-Publication Data

Magdoff, Fred, 1942-
Building soils for better crops : sustainable soil management / by Fred Magdoff and Harold van Es. -- 3rd ed.
p. cm. -- (Handbook series ; bk. 10)
Includes bibliographical references and index.
ISBN 978-1-888626-13-1
1. Soil management. 2. Humus. I. Van Es, Harold, 1958- II. Sustainable Agriculture Research & Education (Program) III. Title. IV. Series: Sustainable Agriculture Network handbook series ; bk. 10.
S592.8.M34 2009
631.4--dc22
2009031856

Authors: Fred Magdoff and Harold van Es
Contributing Writer (farmer profiles): Amy Kremen
Production Manager: Dena Leibman
Copy Editing: Jill Mason
Graphic Design: Kirsten Ankers
Cover Illustration: Frank Fretz
Indexing: Jill Mason
Printing: Printed by United Book Press on process-chlorine-free, 100% post-consumer-waste paper.

CONTENTS

ABOUT THE AUTHORS



Fred Magdoff is emeritus professor of plant and soil science at the University of Vermont and adjunct professor at Cornell University. He was Plant and Soil Science Department chair for eight years and for two decades was the coordinator of the twelve-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. 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, Vermont, with his wife, dog, two cats, a large garden, an occasional flock of chickens, and a small herd of beef cows.

Harold van Es is a professor of soil science at Cornell University and serves as chair of the Department of Crop and Soil Sciences. Born in Amsterdam, Netherlands, he grew up in an environment where soil and water are critical issues. His current research focuses on soil health, computational agriculture, and environmental statistics. He teaches courses in soil management and space-time statistics and also leads an extension program. He is a fellow of the Soil Science Society of America and the American Society of Agronomy. He lives in Lansing, New York, with his wife, three children, and two cats.

SARE
Sustainable Agriculture
Research & Education

ABOUT SARE

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 5,000 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, and coordinators in every state and island protectorate run education programs for ag professionals. SARE Outreach publishes practical books, bulletins, online resources, and other information for farmers and ranchers. All of SARE's activities are funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture.

Guided by the belief that healthy soil is the foundation of healthy agriculture, SARE has made soil quality research and education a cornerstone of its project portfolio—and made *Building Soils for Better Crops* one of its signature handbooks. This new, all-color edition is an authoritative text on soil health, detailing the latest research and experiences of soil scientists—many of whom are SARE grant participants, including the book's authors. Some other SARE titles that might be of interest to *Building Soils* readers: (Books) *Managing Cover Crops Profitably*, third edition; *The New American Farmer*, second edition; *Crop Rotation on Organic Farms*; (Bulletins) *Diversifying Cropping Systems*; *Transitioning to Organic Production*; and *Smart Water Use on Your Farm or Ranch*.

For more information about SARE's grant-making program and information products, visit www.sare.org or contact: SARE Outreach, 1122 Patapsco Bldg., University of Maryland, College Park, MD 20742-6715; info@sare.org; (301) 405-8020.

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. *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. 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 withstand droughty conditions better 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.

Organic matter management was also the heart of the second edition, but we decided to write a more comprehensive guide that includes other essential aspects of building healthy soils, such as managing soil physical properties and nutrients, as well as a chapter on evaluating soil health (chapter 22). In addition, we updated farmer case studies and added a new one. The case studies describe a number of key practices that enhance the health of the farmers' soils.

Many chapters were rewritten, expanded, and reorganized for the third edition—some completely. A chapter on physical properties and issues was divided into two (chapters 5 and 6), and chapters were added on the principles of ecological soil management (chapter 8) and on irrigation and drainage (chapter 17). The third edition, while still focusing on farming and soils in the United States, has a broader geographical scope; the book has evolved into a more comprehensive treatise of sustainable soil management for a global audience. We have, however, maintained the use of English units in the book for the convenience of our original target audience, although many readers outside North America—and scientists like us—would perhaps prefer the use of metric units.

A book like this one cannot give exact answers to problems on specific farms. In fact, we are purposely staying away from recipe-type 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 needs to be adaptive and is better achieved through education and understanding than with simple recommendations.

Over many centuries, people have struggled with the same issues 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 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 contains the blueprints for modern seed drills. 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 or the entire manuscript at one stage or another and made very useful suggestions. We would like to thank George Abawi, William Brinton, Andy Clark, Bill Cox, Karl Czymmek, Heather Darby, Addy Elliott, Charles Francis, Tim Griffin, Joel Gruver, Karl Hammer, Jon Hanson, Ellen Harrison, John Havlin, Robert L. Hill, Bruce Hoskins, Bill Jokela, Doug Karlen, Ann Kennedy, Charles Mitchell, Jr., Tom Morris, John Peters, Stu Pettygrove, Marianne Sarrantonio, John Sawyer, Eric Sideman, Gene Stevens, Jeff Strock, and Ray Weil.

We recognize colleagues who provided photos in the figure captions, and we are grateful for their contribution. All other photos are our own or in the public domain. We also acknowledge some of our colleagues—Bob Schindelbeck, George Abawi, David Wolfe, Omololu (John) Idowu, Ray Weil, and Rich Bartlett (deceased)—whose ideas and insights 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.

— Fred Magdoff
Professor Emeritus
Department of Plant & Soil Science
University of Vermont

— Harold van Es
Professor and Chair
Department of Crop & Soil Sciences
Cornell University

June 2009

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 iPod, 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 occurred. Many civilizations have collapsed from unsustainable land use, including the cultures of the Fertile Crescent in the Middle East, where the agricultural revolution first occurred about 10,000 years ago. The United Nations estimates that 2.5 billion acres have suffered erosion since 1945 and that 38% of global cropland has become seriously degraded since then. In the past, humankind survived because people developed new lands. But a few decades ago the total amount of agricultural land actually began to decline as new land could no longer compensate for the loss of old land. The exhaustive use of land is combined with increasing populations; greater consumption of animal products produced in large-scale facilities, which creates less efficient use of crop nutrients; expanding acreages for biofuel crops; and the spread of urban areas, suburban and commercial development, and highways onto agricultural lands. We have now reached a point where we are expanding into marginal lands—like shallow hillsides and arid areas—that are very fragile and can degrade rapidly (figure I.1). Another area of agricultural expansion is virgin tropical rainforests, which are the last remnants of unspoiled and biologically rich land. 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 out of land. We have already seen hunger and civil strife—especially in Africa—over limited land resources and productivity, and a global food crisis break out in 2008. Some countries with limited water or arable land are purchasing or renting land in other countries to produce food for the "home" market.

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

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, which have resulted in food security for much of the developed world. At the same time, mechanization and the ever-increasing capacity of field equipment allow farmers to work increasing acreage. 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, the increase in the price of energy—as well as the diversion of crops to produce ethanol and biodiesel and other trends—will cause food prices to be higher in the future, resulting in a worldwide upsurge in hunger.

- Too much nitrogen fertilizer or animal manure sometimes causes high nitrate concentrations in groundwater. These concentrations can become high enough to pose a human health hazard. Many of the biologically rich estuaries and the parts of seas near river inflows around the world, including the Gulf of Mexico, 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 water bodies and degrade their quality by stimulating algae growth.
- Antibiotics used to fight diseases in farm animals 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 the silting up of reservoirs, ponds, and lakes.
- Soil compaction reduces water infiltration and increases runoff, thereby increasing flooding, while at the same time making soils more drought prone.
- In some parts of the country groundwater is being used for agriculture faster than nature can replenish this invaluable resource. In addition, water is increasingly diverted for urban growth in dry regions of the country, lessening the amount available for irrigated agriculture.

The whole modern system of agriculture and food is based on extensive use of fossil fuels—to make and power large field equipment, produce fertilizers and pesticides, dry grains, process food products, and transport them over long distances. With the price of energy so much greater than just a few years ago, the economics of the "modern" agricultural system may 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 and plant diseases can be found in foods, animal feeds, groundwater, and surface water running off agricultural fields. Farmers and farm workers are at special risk. Studies have shown higher cancer rates among those who work with or near certain pesticides. Children in areas with significant usage of pesticides are also at risk of having developmental problems. When considered together, these inadvertent by-products of agriculture are huge. The costs of all these negative effects on wildlife, natural resources, human health, and biodiversity in the United States is estimated at 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. As consolidations and other changes occur in the agriculture input (seeds, fertilizers, pesticides, equipment, etc.), food processing, and marketing sectors, the farmer's bargaining position weakens. 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. At the time of writing this edition, the prices for many agricultural commodities have recently seen sharp increases and then a rapid decrease. On the other hand, the costs of purchased inputs also increased greatly but then did not decrease as much as crop prices did. The wide swings in prices of crops and animal products have created a lot of stress among farmers.

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 the consumer, they frequently find that there are ways to increase profitability by decreasing the use of inputs purchased off the farm and selling direct to the end-user.

SOIL HEALTH INTEGRAL TO SUSTAINABLE AGRICULTURE

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. 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 the cycling of nutrients 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 the availability of cheap water for irrigation in some parts of the western United States, many people working with soils forgot or ignored the importance of organic matter in promoting high-quality soils.

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

As farmers and scientists were placing less emphasis on soil organic matter during the last half of the 20th century, farm machinery was 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 use of the moldboard plow, followed by harrowing, broke down soil structure and left no residues on the surface. Soils were left bare and very susceptible to wind and water erosion. New harvesting machinery was developed, replacing hand harvesting of crops. As dairy herd size increased, farmers needed bigger spreaders to handle the manure. More passes through the field with heavier equipment to spread fertilizer and manure, prepare a seedbed, plant, spray pesticides, and harvest created the potential for significant amounts of 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 react after seeing a "problem" in the field. If a soil is deficient in some nutrient, you buy a 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 an implement, such as a subsoiler, to tear it open. If a plant disease or insect infestation occurs, you apply a pesticide.

Are low nutrient status; poor water-holding capacity; soil compaction; susceptibility to erosion; and disease, nematode, or insect damage 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 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.

What many people think are individual problems may just be symptoms of a degraded, poor-quality soil. These symptoms are usually directly related to depletion of soil organic matter, lack of a thriving and diverse population of soil organisms, and compaction caused by use of heavy field equipment. Farmers have been encouraged to react to individual symptoms instead of focusing their attention on general soil health management. A new approach is needed to help develop farming practices that take advantage of the inherent strengths of natural systems. In this way, we can prevent the many symptoms of unhealthy soils from developing, instead of reacting after they develop. If we are to work together with nature, instead of attempting to overwhelm and dominate it, the buildup and maintenance of good levels of organic matter in our soils are as critical as management of physical conditions, pH, and nutrient levels.

A skeptic might argue that the challenges described above are simply the result of basic economic forces, including the long-run inexpensive cost of fossil fuel and crop inputs (although this is changing), and the fact that environmental consequences and long-term impacts are not internalized into the economic equation. It could then be argued that matters will not improve unless the economic incentives are changed. We argue that those economic motivations are already present, 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.

This book has four parts. Part 1 provides background information about soil health and organic matter: what it is, why it is so important, 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 nutrient cycles and flows. Part 3 deals with the ecological principles behind—and 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. Burlington: University of Vermont, College of Agriculture.

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

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

ORGANIC MATTER—THE KEY TO HEALTHY SOILS

PART 1

Photo by Dennis Nolan