Published 2009

Organic Farming: The Ecological System

Organic Farming: The Ecological System

Charles Francis, Editor

Agronomy Monograph 54

American Society of Agronomy
Crop Science Society of America
Soil Science Society of America

American Society of Agronomy, Inc.
Crop Science Society of America, Inc.
Soil Science Society of America, Inc.
677 South Segoe Road, Madison, WI 53711-1086 USA

Reprinted in 2010.

ISBN: 978-0-89118-173-6

Library of Congress Control Number: 2009909959

Cover design: Patricia Scullion

Cover photos: Images from the Center for Environmental Farming Systems, Raleigh; NC. Ken Wolf Photography, Raleigh, NC. Carrot photo, iStockphoto.com

Printed on recycled paper.
Printed in the United States of America.

Contents

Foreword

The science of crop production has advanced considerably with increased understanding of genetics, cellular biology, cellular physiology, soil plant interfaces, nutrient uptake, pest interactions, stress physiology, systems biology, ecology, soil water relations, economics, and basic soil and crop sciences. The application of this knowledge to organic crop production has been relatively limited in terms of years and volume of research, but significant new information has been obtained in the past 20 years as organically produced crops have increased to more than 2% of our food consumption in the United States.

Attention to organic farming practices and systems by state, federal, and nonprofit research groups has been welcomed by the organic farming community. Long dependent mainly on farmer experiences, those who produce organic crops and livestock are now working together with scientists to uncover mechanisms and better understand how nonchemical methods work. This collaboration of researchers with farmers is a good example of the potential for cooperative research that is important in advancing our knowledge in this emerging sector of the food system. The focus on ecology of farming is an essential foundation for understanding systems and improving production.

During the past five years the amount of research has increased considerably, with a significant increase in federal funding for organic research. We have seen an increased number of presentations and posters on organic research at the past several ASA–CSSA–SSSA meetings and more publications in our major journals. The Societies' Book and Multimedia Publishing Committee has observed this growth, and yet observed that there is no general reference work on organic production in the United States that is comprehensive and suitable as a college textbook that brings all the elements together. This led us to solicit an editor to develop such a reference. We appreciate the willingness of Dr. Charles Francis, of the University of Nebraska Agronomy and Horticulture Department, to take the lead and work with colleagues in this effort. His research and teaching in sustainable systems and special focus on organic production, along with his interactions with the organic farming community, make him an appropriate editor. The efforts by experts to develop the theme for each chapter and the excellent work by Society staff to transform the manuscript into an outstanding publication are easily recognized.

While much is controversial in the comparisons of organic and non-organic systems, those students, farmers, and scientists who are interested in learning more about the practices that lead to successful certification will find this new reference to be invaluable. For instructors offering courses in organic crop and animal production this would serve well as a textbook or reference book. A definitive work such as *Organic Farming: The Ecological System* will set the stage for research, extension, and education for many years to come.

David D. Baltensperger
Professor and Head of the Department, Soil and Crop Sciences, Texas A&M University
ASA–CSSA–SSSA Book & Multimedia Publishing Committee Chair

Preface

Agriculture is going through a profound revolution, one that rivals the industrial revolution of the 19th century and the green revolution in the 20th century. These previous changes transformed industries based primarily on local resources and principally serving local markets to more complex systems using high levels of technology. These have evolved to become more fossil fuel intensive, less efficient in output per unit energy input, and more global in their markets. Some people define current agricultural changes only in terms of specific technologies, such as transgenic crops and site-specific input use determined by GPS spatial methods. Yet there is a more profound change taking place mostly at the grass roots—a recognition that the resilience and sustainability of ecology and natural systems have much to teach modern agriculture. Organic farming systems are one manifestation of this new awareness.

Over the past decade, worldwide sales of organic crop and livestock products have expanded 10 to 20% per year (Lockie et al., 2006; Greene and Dimitri, 2007; Organic Trade Association, 2007), increasing interest in organic farming as a potentially profitable and more environmentally benign alternative to conventional production methods. Sales of organic products in 2006 exceeded $16 billion in the United States and reached $40 billion globally, with no drop in this market expected in the near future (U.N. Food and Agriculture Organization, 2007). Prices at the farm gate for organic products may be 10 to 300% greater than for conventional products. In spite of this price differential, sale of organic food continues to grow in the United States, Europe, Japan, and elsewhere. Matt Liebman and Adam Davis, co-authors of Chapter 8, provide a useful overview delving into this intriguingly counter-intuitive economic situation.

To participate in the current food system, it is imperative that agronomists and horticulturists master the practices, systems design, certification process, and details of that system's organic farming sector. The last American Society of Agronomy (ASA) book on organic farming was published more than two decades ago (Bezdicek and Power, 1984); to say that much has happened in research and development since that publication would be a gross understatement. Combining farmer experience and wisdom with the best that science has to offer can lead us to a better understanding of organic systems' mechanisms, as well as how we can design them to both meet human needs and preserve an environment where we would like to live. Beyond their production, economics, and environmental impacts, we are also learning that organic farming and food systems have potential to revitalize the rural landscape and its communities—areas that, as a result of industrial agriculture, are currently highly exploited, depopulated to some degree, and lacking in essential human and ecosystem services on which our long-term well-being depends.

In a series of integrated chapters by people in academic and nonprofit groups working on organic farming and food systems, we present a window on current research and development and a glimpse of a more desirable future for us all. We recognize up front that much of both innovation and application of organic farming methods have come from farmers, and that as researchers we build on this legacy in the United States, Europe, and elsewhere. This book represents a current look at what we know about organic farming practices and systems, primarily from the U.S. and Canadian perspectives.

A brief history of organic farming and an overview of the legal certification process in the U.S. are presented in Chapter 1 by Charles Francis and Justin Van Wart. The rapid standardization of products and their labeling were necessary steps in the growth of organic food markets, yet they introduce a number of challenges, since those efforts led much of our organic production and sales to resemble the industrial model. The ecological tone of the book is set by Laurie Drinkwater from Cornell University in Chapter 2, where she explores the importance of ecological knowledge as the foundation for not only organic farming but for sustaining food systems into the future. Studies of organic systems require holistic research strategies that can differ from traditional experimental design.

Careful systems design is essential for successful organic farming. One of the key practices that reflects the essential biodiversity needed in farming systems is crop rotation, whose principles and specific examples are described in Chapter 3 by Paul Porter from University of Minnesota. Natural systems are characterized by plants and animals, and the closest we can come in agriculture is to design crop–animal systems that are tightly integrated on the farm, a topic discussed in Chapter 4 by Martin Entz and J.R. Thiessen Martens from Manitoba. The essential role of forages in these complex farming systems is presented in Chapter 5 by E. Ann Clark of Guelph University in Ontario. How major grain, oil seed, and specialty crops are grown and marketed organically in the United States is described in Chapter 6 by Kathleen Delate of Iowa State University.

Specific organic practices are explored in the next section on soil fertility and pest management. Joseph Heckman of Rutgers University, Ray Weil of University of Maryland, and Fred Magdoff from University of Vermont are three of the best informed and most prolific authors on the subject of organic cropping and soil nutrient needs, a topic they present in Chapter 7. Innovative nonchemical methods for vegetation management in cropping systems are described in Chapter 8 by Matt Liebman of Iowa State University and Adam Davis of ARS/USDA in Urbana, Illinois. Understanding the biology of pests is critical to managing their impacts on crop plants; George Bird and colleagues from Michigan State University and Rodale Research Center provide an overview of pest classification and alternatives for pest management in Chapter 9.

Marketing of organic products is an essential part of the food chain or food web that will provide farm profits and lead to changes in the food system. In Chapter 10 Agricultural economist Hikaru Hanawa Peterson and horticulturist Rhonda Janke from Kansas State University describe the complexities and innovations that characterize the marketing of organic products in this fast-growing segment of the food industry. Sociologists Patricia Allen and Hilary Melcarek of U.C. Santa Cruz have published widely on the social impacts of alternative food systems and provide an overview of organic foods and food security in Chapter 11.

Organic research, teaching, and extension programs are new ventures for most of our land-grant universities, although they have been vital to informal education for decades. Nancy Creamer and colleagues describe in Chapter 12 the highly successful, integrated, and multi-institutional program in organic and sustainable agriculture research in North Carolina. Chapter 13, contributed by myself, Charles Francis from University of Nebraska, explores the growth of education and extension in organics, including the important roles played by farmers and by nonprofit organizations in the United States. Chapter 14, also contributed by myself, surveys the future of organic farming and the major challenges and changes we are seeing in this sector. Finally, a perspective on the overall structure of the agricultural industry and the future of the rural sector is envisioned in Chapter 15 by Fred Kirschenmann, a North Dakota farmer and active leader at Iowa State University.

These scholarly chapters describe the past, present, and future of organic farming in the U.S. and Canada. We recognize the parochial coverage of this important topic, as there are limited references to and no contributions from scientists and educators in Europe, from the Indian sub-continent, and other important centers of organic research and development. There are also many innovative consumer-driven marketing strategies, for example the large organic consumer network in Japan. Countries in the Nordic Region and some in northern Europe have set specific national goals to achieve a certain level of organic food by a specific year. There are also important advances being made in emerging economies, where in fact much of the farming is de facto organic due to the lack of chemical pesticide and fertilizer inputs. We recognize these initiatives and urge the serious reader to explore this wide range of activities through research or through travel and personal experience.

Organic Farming: The Ecological System provides a snapshot of programs and some history of development of this emerging part of local and global food systems. There will be many changes in the near future as a result of increasing economic pressures, growing appreciation of the impacts of chemicals on our food supply, livestock and human health, and understanding of how the structure of agriculture impacts the quality of life in the rural landscape and the ecosystem services available to us all. As a team of authors, we urge the American Society of Agronomy to continue to provide timely and relevant updates in this important area of agriculture.

Charles Francis, Editor

References

Bezdicek, D.F., and J.F. Power (ed.) 1984. Organic farming: Current technology and its role in a sustainable agriculture. ASA Spec. Publ. 46. ASA, CSSA, SSSA, Madison, WI.

Greene, C., and C. Dimitri. 2007. Organic agriculture: Consumer demand continues to expand. Available at http://www.ers.usda.gov/Briefing/Organic/Demand.htm (accessed 29 Nov. 2007, verified 2 Sept. 2009). USDA-Economic Research Service, Washington, DC.

Lockie, S., D. Halpin, and D. Pearson. 2006. Understanding the market for organic food. p. 245–258. *In* P. Kristiansen et al. (ed.) Organic agriculture: A global perspective. Comstock Publishing, Ithaca, NY.

Organic Trade Association. 2007. Organic Trade Association's 2007 Manufacturer Survey. Available at http://www.ota.com/pics/documents/2007ExecutiveSummary.pdf (accessed 29 Nov. 2007, verified 2 Sept. 2009). OTA, Greenfield, MA.

U.N. Food and Agriculture Organization. 2007. Report of the International Conference on Organic Agriculture and Food Security, Rome, Italy. 3–5 May 2007. Available at ftp://ftp.fao.org/docrep/fao/meeting/012/j9918e.pdf (accessed 29 Nov. 2007, verified 2 Sept. 2009). FAO, Rome.

Contributors

Patricia Allen is Director of the Center for Agroecology and Sustainable Food Systems at the University of California–Santa Cruz. Her research interests include the political ecology of agrifood systems; alternative agrifood institutions; the social construction and relationships among nature, environment and society, race, class, and gender issues in the agrifood system; and the political economy of alternative modes of distribution and consumption and public health.

Ctr. for Agroecology and Sustainable Food Systems, Univ. of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064 (PatriciaAllen@ucsc.edu)

George Bird is Nematologist and Professor of Entomology at Michigan State University, where he also coordinates diagnostic services as an extension specialist. He has been Coordinator of the North Central Sustainable Agriculture Research and Education program, and served as National Coordinator of this program for the USDA. George also coordinates the IPM program at Michigan State and is on the board of directors of Rodale Institute.

Dep. of Entomology, Michigan State Univ., 38A Natural Sci., East Lansing, MI 48824 (birdg@msu.edu)

E. Ann Clark has teaching and research interests in pasture and grazing management, and in the design of ecologically sound production systems. She is Associate Professor in Plant Agriculture at the University of Guelph, Ontario, Canada. One of her prominent books is *The Contribution of Managed Grasslands to Sustainable Agriculture in the Great Lakes Basin*, published by Haworth Press in 1996.

Dep. of Plant Agriculture, Univ. of Guelph, Crop Science Bldg., 50 Stone Rd. E., Guelph, ON, Canada N1G 2W1 (eaclark@uoguelph.ca)

Nancy Creamer specializes in farming systems research, cover cropping and weed management in organic production systems, and community-based sustainable local food systems. She is Director of the Center for Environmental Farming Systems, a cooperative center organized in collaboration with North Carolina A&T and other groups, and currently a major source of education and research-based information on organic farming and sustainable agriculture. She is Extension Specialist and Professor of Horticulture at North Carolina State University.

Ctr. for Environmental Farming Systems, North Carolina State Univ., Campus Box 7609, Raleigh, NC 27695 (nancy_creamer@ncsu.edu)

Adam Davis is a weed ecologist with the USDA-ARS Invasive Weed Management Unit in Urbana, Illinois. His research centers on integrating empirical and theoretical approaches to multi-tactic management of weedy and invasive plant species. He is also Assistant Professor, Crop Sciences, and a member of the faculty of the Program in Ecology and Evolutionary Biology, University of Illinois.

USDA-ARS, Invasive Weed Management Unit, N-319 Turner Hall, Univ. of Illinois, 1102 S. Goodwin Ave., Urbana, IL 61801 (asdavis1@illinois.edu)

Kathleen Delate was appointed to the first land-grant university faculty position in organic agriculture in the U.S. in 1997. She is currently Associate Professor at Iowa State University in Horticulture and Agronomy Departments, where she is responsible for research, extension, and teaching in organic agriculture. Kathleen has farmed organically in Florida, Hawaii, California, and Iowa. She has degrees in agronomy, horticulture, and agricultural ecology.

Dep. of Agronomy and Horticulture, Iowa State Univ., 106 Horticulture Hall, Ames, IA 50011 (kdelate@iastate.edu)

Laurie Drinkwater is Agroecologist and currently Associate Professor in the Department of Horticulture, Cornell University. Her research focuses on nitrogen, carbon, and phosphorus biogeochemistry, and the ecology of agriculture and development of sustainable food systems. She has been engaged in ecological research on organic agriculture since the late 1980s.

Dep. of Horticulture, Cornell Univ., Plant Science Bldg., Rm. 124, Ithaca, NY 14853 (led24@cornell.edu)

Martin Entz is Professor of Cropping Systems at the University of Manitoba. He has education and research experience in crop physiology, agronomy, and organic agriculture. Included in his research are experiments on crop rotation benefits, long-term organic vs. conventional comparisons, cover crops, crop production energy efficiency, and integrated crop–livestock systems.

Dep. of Plant Science, Univ. of Manitoba, Winnipeg, MB, Canada, R3T 2N2 (m_entz@umanitoba.ca)

Charles Francis is Professor of Agronomy and Horticulture at University of Nebraska–Lincoln. His education and field experience in plant breeding and agronomy in the United States and in developing countries has led to research on crop rotations, genotype by systems interactions, multifunctional rural landscapes, and peri-urban farming. He has an appointment in research, teaching, and extension, and teaches agroecology, organic farming, and urbanization of rural landscapes, a course dedicated to education on the long-term impacts of urban sprawl.

Dep. of Agronomy and Horticulture, Univ. of Nebraska, 279 Plant Science, Lincoln, NE 68583-0915 (cfrancis2@unl.edu)

Matthew Grieshop is Assistant Professor of Entomology and Organic Pest Management Specialist in research and extension at Michigan State University. He specializes in integrated pest management and is active in the Fruit and Vegetable Area of Excellence teams in Cooperative Extension.

Dep. of Entomology, Michigan State Univ. 38A Natural Science, East Lansing, MI 48824 (grieshop@msu.edu)

Joseph Heckman is Professor of Soil Science at Rutgers University in the Department of Plant Biology and Pathology and has an interest in the history of organic agriculture. He grew up on an Ohio farm where his family began farming organically around 1949. He teaches courses in Soil Fertility and Organic Crop Production, and has research and extension programs with a focus on soil fertility management of agronomic and horticultural crops. He serves as Chair of the Committee on Organic and Sustainable Agriculture.

Dep. of Plant Biology and Pathology, Cook College, Rutgers, The State Univ. of New Jersey, 59 Dudley Rd., Foran Hall, New Brunswick, NJ 08901-8520 (heckman@AESOP.rutgers.edu)

Paul Hepperly is research and training director of the Rodale Institute in Kutztown, Pennsylvania. His background is in psychology, agronomy, and plant pathology, and his current research is focused on organic methods of pest management and carbon sequestration. His past experience includes work on temperate and tropical crops in Hawaii, India, Puerto Rico, and Chile, and he has also worked for the USDA and for commercial seed companies.

Rodale Research Inst., 611 Siegfriedale Rd., Kutztown, PA 19530-9320 (paul.hepperly@rodaleinst.org)

Laurie Hodges is Associate Professor of Agronomy and Horticulture at University of Nebraska–Lincoln. She has conducted research on the effects of microclimate on vegetable and cut flower crops and herbicide effects on root exudates and soil-borne pathogens. She works with large- and small-scale commercial producers on cultural practices to increase yield and profitability in high tunnel and field production systems. Her appointment is in extension and research with frequent invitations to speak with students and the public about her experiences with organic production systems and direct marketing.

Dep. of Agronomy & Horticulture, 279 Plant Science Bldg., Univ. of Nebraska, Lincoln, NE 68583-0910 (lhodges1@unl.edu)

Rhonda Janke is Associate Professor in the Department of Horticulture, Forestry, and Recreation Resources at Kansas State University, with research and extension experience in sustainable and organic cropping systems, weed ecology, whole farm planning, alternative crops, and soil quality. She currently teaches fruit crops, vegetable crops, sustainable agriculture, and organic farming systems. Her interest in local and organic food systems includes both extension activities and personal experience as a small-scale organic fruit and vegetable grower.

Dep. of Horticulture, Forestry, and Recreation Resources, Kansas State Univ., 2021 Throckmorton, Manhattan, KS 66506 (rrjanke@ksu.edu)

Fred Kirschenmann is former Director and currently Distinguished Fellow at the Leopold Center, Iowa State University, and President of the Stone Barns Center. He is one of the most articulate and highly recognized leaders in the U.S. in issues related to organic farming and sustainable agriculture and food systems. He is active in the Agriculture of the Middle initiative, which works to promote the future of mid-sized family farms, and he continues to own and co-manage a 3500-acre organic farm in North Dakota.

Leopold Ctr. for Sustainable Agriculture, 209 Curtiss Hall, Iowa State Univ., Ames, IA 50011-1050; Stone Barns Ctr. for Food and Agriculture, Pocantico Hills, NY (leopold1@iastate.edu)

Matt Liebman is Professor of Agronomy and the Henry A. Wallace Endowed Chair for Sustainable Agriculture at Iowa State University. His research, teaching, and outreach activities focus on reducing dependency on agrichemicals and fossil fuels through ecological processes. Included in his research are experiments focused on diversified cropping systems, organic soil amendments, and weed population dynamics.

Dep. of Agronomy, Iowa State Univ., 1401 Agronomy Hall, Ames, IA 50011-1010 (mliebman@iastate.edu)

Fred Magdoff is Professor Emeritus of Plant and Soil Science, University of Vermont and Adjunct Professor in the Department of Crop and Soil Sciences at Cornell University. For many years he taught and conducted research in the area of soil fertility. He was also a member of the National Small Farm Commission and Director of USDA's Northeast Region Sustainable Agriculture Research and Education Program. He is co-author of *Building Soils for Better Crops, a guide to ecological soil management*, SARE, 2000.

Dep. of Plant and Soil Science, Univ. of Vermont, Hills Bldg., Burlington, VT 05405 (fmagdoff@uvm.edu)

Hilary Melcarek has an interdisciplinary academic background in natural resource management and is currently studying urban agriculture in relation to urban social movements. She is a graduate student researcher and doctoral candidate in the Environmental Studies Department at the University of California–Santa Cruz.

Ctr. for Agroecology and Sustainable Food Systems, Univ. of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064 (melcarek@ucsc.edu)

Jeff Moyer is the Farm Director of the Rodale Research Institute near Kutztown, Pennsylvania. He has recently been appointed as chair of the USDA National Organic Standards Board, the official board that oversees the U.S. National Organic Program. As Farm Manager, Jeff has innovated with organic crop rotations and cover crops, as well as specialized equipment such as a roller-crimper to help manage cover crops before incorporation into the soil. He brings to the book years of farming knowledge, and a wide range of experiences with farmers converting to organic systems.

Rodale Research Inst., 611 Siegfriedale Rd., Kutztown, PA 19530-9320
(jeff.moyer@rodaleinst.org)

J. Paul Mueller has research and extension experience in applied grassland farming research with ruminant animals, including caprine silvo-pastoral systems and agricultural systems that integrate crops and livestock. He is interim Assistant Dean of International Programs, Sustainable Agriculture Coordinator for the College of Agriculture and Life Sciences, and Coordinator of the Farming Systems Research Unit, all at North Carolina State University.

Office of International Programs, College of Agriculture and Life Sciences, North Carolina State Univ., 319 Scott Hall, Campus Box 7608, Raleigh, NC 27695-7608
(Paul_Mueller@ncsu.edu)

John O'Sullivan has expertise in farm management, marketing, community-based food systems, and evaluation. He is coordinator of the Small Farm Unit at CEFS and a Farm Management and Marketing Extension Specialist. He is Adjunct Professor in the Department of Agricultural Economics at North Carolina Agricultural and Technical State University.

Ctr. for Environmental Farming Systems, North Carolina A&T State Univ., P.O. Box 21928, Greensboro, NC 27420 (Johno@ncat.edu)

Hikaru Hanawa Peterson is an agricultural economist whose research focuses on understanding marketing and risk management decisions in food and agriculture. Previous studies have examined marketing issues related to small-scale specialty crops, large-scale commercial crops, the dairy and livestock sectors, and the organic industry. She currently teaches agricultural marketing and agricultural finance at Kansas State University.

Dep. of Agricultural Economics, Kansas State Univ., 318 Waters Hall, Manhattan, KS 66506
(hhp@ksu.edu)

Paul Porter has research and education experience in agronomy in the United States, Zaire, and elsewhere, with a focus on crop rotation and the rotation effect, alternative cropping systems involving rye as a cover crop, and alternative crops. He is Professor of Agronomy and Plant Genetics at the University of Minnesota–St. Paul, with responsibilities in research and teaching, including a popular summer experiential learning course in agroecosystems analysis.

Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, 411 Borlaug Hall, 1991 Buford Circle, St. Paul, MN 55108 (pporter@umn.edu)

Chris Reberg-Horton works on weed management in organic soybeans, introducing legume cover crops into corn–soybean–wheat rotations, reducing tillage in organic systems, allelopathic cover crops, and creating market opportunities for organic producers. He chairs the Organic Farm Panel, the Allelopathy Working Group, and the Organic Research Unit at the Center for Environmental Farming Systems and is an Assistant Professor and Organic Cropping Specialist at North Carolina State University.

Dep. of Crop Science, North Carolina State Univ., Campus Box 7620, Raleigh, NC 27695-7620
(chris_reberg-horton@ncsu.edu)

Michelle Schroeder-Moreno is an ecologist with interests in tropical biology and application of ecological principles in a variety of agricultural ecosystems. Her investigations have included examining how arbuscular mycorrhizal fungi mediate competition among crops in monocultures and polycultures and how phosphorus fertilizers reduce crop growth responses to arbuscular mycorrhizal fungi. She coordinates the Agroecology Program and teaches agroecology courses as Teaching Assistant Professor at North Carolina State University.

Crop Science Dep., North Carolina State Univ., 2406 Williams Hall, Campus Box 7620, Raleigh, NC 27695-7620 (michelle_schroeder@ncsu.edu)

Joanne Thiessen Martens is a Research and Extension Associate with the Organic Agriculture Centre of Canada, based at the University of Manitoba. She is involved in cover crop research, writing research papers and extension materials, and maintaining and developing the Natural Systems Agriculture Website. Her primary assignment involves facilitating the flow of information between organic researchers and organic producers.

Dep. of Plant Science, Univ. of Manitoba, Winnipeg, MB, Canada, R3T 2N2 (j_thiessen_martens@umanitoba.ca)

Justin Van Wart has academic study in agricultural economics and agronomy, and experience in linguistics and agricultural development in other countries. He is currently a graduate research assistant and doctoral candidate in the Department of Agronomy and Horticulture at University of Nebraska–Lincoln, working on biology and economics of energy relationships in biofuels, peri-urban agriculture, and organic farming systems.

Dep. of Agronomy and Horticulture, Univ. of Nebraska, 279 Plant Science, Lincoln, NE 68583-0915 (justin.vanwart@huskers.unl.edu)

Steve Washburn is a dairy scientist whose focus is reproductive management of dairy and beef cattle herds, seasonal breeding, crossbreeding in dairy cattle, estrous synchronization, and pasture-based and organic dairy production systems. He is Coordinator of the pasture-based Dairy Unit at CEFS and a Professor and Extension Specialist in the Animal Science Department at North Carolina State University.

Dep. of Animal Science, North Carolina State Univ., 211-C Polk Hall, Box 7621, Raleigh, NC 27695-7621 (Steve_Washburn@ncsu.edu)

Ray R. Weil is Professor of Soil Science in the Department of Environmental Science and Technology at University of Maryland. Since 1972 when he ran a 500-acre organic farm in North Carolina, he has been devoted to researching and promoting sustainable agricultural systems in both developed and developing countries. His research in collaboration with dozens of innovative farmers integrates management of soil organic matter, nutrient cycling, and alternative cropping systems to improve both the soil and the farmer's bottom line. Ray is best known as co-author of the classic soil science textbook, *The Nature and Properties of Soils.*

Dep. of Natural Resource Sciences and Landscape Architecture, Univ. of Maryland, H.J. Patterson Hall, Collegeville, MD 20742 (rweil@umd.edu)

Conversion Factors for SI and Non-SI Units

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
		Length	
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, μm (10^{-6} m)	micron, μ	1.0
3.94×10^{-2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10^{-9} m)	Angstrom, Å	0.1
		Area	
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 $(10^3\ m)^2$	acre	4.05×10^{-3}
0.386	square kilometer, km^2 $(10^3\ m)^2$	square mile, mi^2	2.590
2.47×10^{-4}	square meter, m^2	acre	4.05×10^3
10.76	square meter, m^2	square foot, ft^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 $(10^{-3}\ m)^2$	square inch, in^2	645
		Volume	
9.73×10^{-3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83×10^{-2}
6.10×10^4	cubic meter, m^3	cubic inch, in^3	1.64×10^{-5}
2.84×10^{-2}	liter, L (10^{-3} m^3)	bushel, bu	35.24
1.057	liter, L (10^{-3} m^3)	quart (liquid), qt	0.946
3.53×10^{-2}	liter, L (10^{-3} m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10^{-3} m^3)	gallon	3.78
33.78	liter, L (10^{-3} m^3)	ounce (fluid), oz	2.96×10^{-2}
2.11	liter, L (10^{-3} m^3)	pint (fluid), pt	0.473
		Mass	
2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
1.10×10^{-3}	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907
		Yield and Rate	
0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, lb bu^{-1}	12.87
1.49×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71

Table continued.

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon per acre	9.35
893	tonne per hectare, t ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447
	Specific Surface		
10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001
	Density		
1.00	megagram per cubic meter, Mg m^{-3}	gram per cubic centimeter, g cm^{-3}	1.00
	Pressure		
9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
2.09×10^{-2}	pascal, Pa	pound per square foot, lb ft^{-2}	47.9
1.45×10^{-4}	pascal, Pa	pound per square inch, lb in^{-2}	6.90×10^3
	Temperature		
1.00 (K – 273)	kelvin, K	Celsius, °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F – 32)
	Energy, Work, Quantity of Heat		
9.52×10^{-4}	joule, J	British thermal unit, Btu	1.05×10^3
0.239	joule, J	calorie, cal	4.19
10^7	joule, J	erg	10^{-7}
0.735	joule, J	foot-pound	1.36
2.387×10^{-5}	joule per square meter, J m^{-2}	calorie per square centimeter (langley)	4.19×10^4
10^5	newton, N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter, W m^{-2}	calorie per square centimeter minute (irradiance), cal cm^{-2} min^{-1}	698
	Transpiration and Photosynthesis		
3.60×10^{-2}	milligram per square meter second, mg m^{-2} s^{-1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56×10^{-3}	milligram (H_2O) per square meter second, mg m^{-2} s^{-1}	micromole (H_2O) per square centimeter second, μmol cm^{-2} s^{-1}	180
10^{-4}	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square centimeter second, mg cm^{-2} s^{-1}	10^4
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm^{-2} h^{-1}	2.78×10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75×10^{-2}

Table continued.

Conversion Factors for SI and Non-SI Units

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
	Electrical Conductivity, Electricity, and Magnetism		
10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	0.1
10^4	tesla, T	gauss, G	10^{-4}
	Water Measurement		
9.73×10^{-3}	cubic meter, m^3	acre-inch, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, m^3 h^{-1}	cubic foot per second, ft^3 s^{-1}	101.9
4.40	cubic meter per hour, m^3 h^{-1}	U.S. gallon per minute, gal min^{-1}	0.227
8.11	hectare meter, ha m	acre-foot, acre-ft	0.123
97.28	hectare meter, ha m	acre-inch, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare centimeter, ha cm	acre-foot, acre-ft	12.33
	Concentration		
1	centimole per kilogram, cmol kg^{-1}	milliequivalent per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1
	Radioactivity		
2.7×10^{-11}	becquerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	becquerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01
	Plant Nutrient Conversion		
	Elemental	Oxide	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602