SYSTEMS RESEARCH FOR AGRICULTURE

Innovative Solutions to Complex Challenges

By Laurie E. Drinkwater
with Diana Friedman and Louise Buck

SARE
Sustainable Agriculture Research & Education
HANDBOOK 13

Systems Research for Agriculture

Innovative Solutions to Complex Challenges

SARE Handbook Series 13

By Laurie E. Drinkwater
with Diana Friedman and Louise Buck

Published 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 (NIFA) and the University of Maryland under cooperative agreement number 2012-47001-19681.

To order:

For online orders visit www.sare.org/WebStore.
Call (301) 779-1007 to order by phone with credit card payment.
To pay by check or purchase order, make payable to Sustainable Agriculture Publications and send to:

SARE Outreach Publications
c/o International Fulfillment Corporation
3570 Bladensburg Rd.
Brentwood, MD 20722

Cost:

- $20 for orders of 1-9 books
- $15 for 10-24 books (a 25% discount)
- $10 for 25 or more books (a 50% discount)

Shipping:

- $6.95 for first book (within the United States). Add $2 s/h for each additional book—up to nine books—shipped within the United States.
- For s/h on orders of 10 or more books, call (301) 779-1007 or visit www.sare.org/WebStore.

International orders:

Call (301) 779-1007 or visit www.sare.org/WebStore.

Library of Congress Cataloging-in-Publication Data
Names: Drinkwater, Laurie E., author. | Sustainable Agriculture Research & Education (Program) | National Institute of Food and Agriculture (U.S.)
Title: Systems research for agriculture: innovative solutions to complex challenges / by Laurie E. Drinkwater; with Diana Friedman and Louise Buck.
Other Titles: SARE handbook; 13.
Descriptions: College Park [Md.]: Published by the Sustainable Agriculture Research and Education (SARE) Program, with funding from the National Institute of Food and Agriculture, U.S. Department of Agriculture, 2016. | SARE handbook series; 13 | Includes bibliographical references.
Identifiers: LCCN 2016018714 | ISBN 9781888626162 (pbk.)
Subjects: LCSH: Agricultural systems--Research.
LCC S494.5.S95 D75 2016 | DDC 630.72--dc23
Classification: LC record available at https://lccn.loc.gov/2016018714

Authors: Laurie E. Drinkwater, Diana Friedman and Louise Buck
Production Manager: Diana Friedman and Abigail Massey, SARE
Copy Editing: Anne Altor, Precision Science Editing
Graphic Design: Kirsten Ankers, Citrine Sky Design
Indexing: D'Ann Hamilton-White
Printing: University of Maryland Printing Services
Printed on paper that is 100 percent post-consumer-waste recycled and processed chlorine free.
Cover Photo: Edwin Remsberg

Published in 2016.

About the Author

Laurie Drinkwater is a professor in the School of Integrated Plant Science at Cornell University. She was raised in Key West, Florida and became interested in agriculture while attending graduate school at at the University of California, Davis. Her research focuses on improving the ecological efficiency and sustainability of agricultural systems by studying the mechanisms governing carbon, nitrogen and phosphorous biogeochemistry in agroecosystems at scales ranging from the rhizosphere, where plant–microbial interactions dominate, to the field and landscape scale, where human interventions strongly influence ecosystem processes. The purpose of this research is to improve the ecological efficiency and sustainability of agricultural systems. She teaches courses in agroecology, sustainability science and soil ecology.

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 5,500 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 Outreach publishes practical books, bulletins, online resources and other information for farmers and ranchers. SARE is funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture. For more information, contact: SARE Outreach, 1122 Patapsco Building, University of Maryland, College Park, MD 20742-6715; phone (301) 405-7955; fax (301) 405-7711; info@sare.org; www.sare.org.

SARE Grants for Systems Research

Each SARE region offers a competitive Research and Education grant program, which can be used to fund multiyear, interdisciplinary investigations of agricultural systems. Smaller partnership grants are also available, designed to encourage agricultural professionals to team up with farmers to conduct on-farm research and demonstration projects.

From its very beginning, SARE has regularly funded projects that focus on various parts of agricultural systems. SARE grantees have studied the benefits of soil-protecting cover crops, alternative methods to broad-spectrum chemicals such as Integrated Pest Management (IPM) and biological control, and integrating crops and livestock. Considered "alternative" practices two and a half decades ago, IPM, cover cropping and many other approaches that promote sustainability are far more common now and are well integrated into many mainstream agricultural research projects and operations. This is in large part due to SARE's long-standing commitment to funding innovative research, which alongside changing societal attitudes has led to public pressure for a cleaner food supply and environment.

Over the years, SARE has also funded a handful of full systems projects, including the Sustainable Agriculture Farming Systems Project (SAFS) at the University of California, Davis (p. 35); the Farming Systems Research Unit at the Center for Environmental Farming Systems (CEFS) at North Carolina State University (p. 20); and the University of New Hampshire Organic Dairy Farm Agroecosystem Study (p. 76), all of which are featured as case studies in this handbook. (See Table 3.1 on p. 44 for a list of current agricultural systems projects in the United States, including ones that have received SARE funding.) However, many proposals received by SARE to study full systems have illuminated the fact that, to a large extent, the agricultural research community lacks a common definition of agricultural systems research.

In response, SARE's Southern region funded the development of an advisory handbook to provide a theoretical basis for agricultural systems research and also to serve as a user-friendly guide for researchers, farmers, extension agents, educators, policymakers and other natural and social scientists seeking to implement a systems approach to agricultural research. The result is this handbook, *Systems Research for Agriculture,* which is designed to assist investigators in furthering their understanding of agricultural systems research while providing hands-on guidance through the multiple steps needed to implement such a project.

For more information about SARE grant opportunities, begin by visiting www.sare.org/grants/apply-for-a-grant or contact the appropriate SARE region. Find regional contact information at www.sare.org/about-sare/staff.

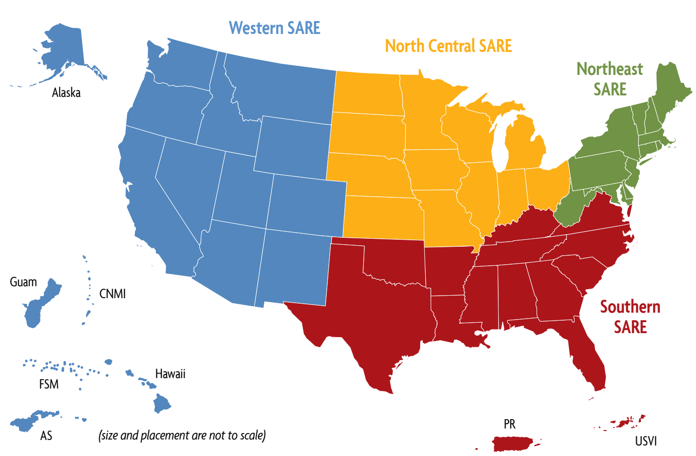


Table of Contents

Preface

Sometimes the questions are complicated and the answers are simple.
—Dr. Seuss

The genesis of this handbook began with a project supported by SARE during the first round of research and education grants the program offered. At the time, I was searching for a way to transition from marine ecology into agricultural research after having recently graduated from University of California, Davis with a PhD in zoology. It was 1988; ecologists in agriculture were still rare and ecology was not widely considered to be relevant to agriculture. When our interdisciplinary team's proposal for an agroecological study comparing organic and conventional vegetable farms in California's Central Valley was selected as one of the first SARE-funded research projects, we were ecstatic. My role in this project set me on a path that eventually led me to write this handbook.

In the course of carrying out this on-farm research I became convinced of the need for much more interdisciplinary, systems-based research to support the transition to sustainable agriculture. In particular, because I was trained in a field where it is commonplace to study real ecological systems, I was astonished by the scarcity of information about how actual farms function as complex ecological systems.

In all the years since, the central challenge of sustainability has not changed. Humanity must find a way to produce abundant, nutritious food without undermining the prospect for future generations to do the same. However, our understanding of what is required to meet this goal has evolved to include fundamental knowledge about ecological and social systems grounded by practical, farmer know-how, and our view of agriculture has expanded to embrace the idea of "multifunctional agricultural systems," a concept that recognizes that farming systems can produce food, fodder and fiber while also providing additional "ecosystem services" to humans. Ecosystem services are the other life-support outcomes produced by the biosphere on which we depend, such as water purification, soil formation, nutrient and water cycling, and climate regulation, to name a few. The revised mission of the USDA reflects this evolution in thinking and recognizes the value of multifunctional agricultural systems in achieving sustainability. Toward that end, environmental conservation, rural development, human nutrition and health, and farm productivity and profitability are all considered to be key goals of agriculture by the USDA and countless institutions involved in the agricultural sector. As a result, the need for systems thinking in agriculture has never been greater. Furthermore, the value of agroecological, systems-based and interdisciplinary research approaches as well as on-farm studies that target these multidimensional goals is now widely recognized.

I hope *Systems Research for Agriculture* will serve as a user-friendly guide for natural and social scientists, extension professionals, educators and policymakers seeking to implement an interdisciplinary, systems approach to agricultural research. I also hope it will be used to help train the next generation of agricultural scientists so that they can draw on this research approach to complement conventional, disciplinary research methods.

Systems Research for Agriculture begins with a brief introduction to the theoretical basis for agricultural systems research, followed by detailed, step-by-step guidance on how to form effective interdisciplinary teams and design and carry out systems research, with an emphasis on interdisciplinary projects. Conducting systems research is not like baking a cake, so there is no specific recipe for success. Instead, I have tried to provide many examples to illustrate the diverse range of strategies that have been used in effective systems projects. The topic of systems research in agriculture is vast and growing at a rapid rate. I feel that I have only captured the most basic information, despite all the work that has gone into this book. There simply was not room to cover everything, so I have tried to provide a reasonable list of additional resources to supplement this handbook.

The original intention was to develop a short booklet on this subject, but during the writing process it grew into an ambitious handbook of five chapters. Along the way, many people made important contributions, and I am indebted to all of them. I am grateful to Southern SARE and Dr.

Jeffrey Jordan for recognizing the need for this handbook and funding the early stages of the work. His foresight made it possible to begin this project, by enabling me to gather experiences from many different people early on in the writing process. As a result, *Systems Research for Agriculture* contains the collective experiences of many of the nation's leading agricultural systems researchers. I am also grateful to Louise Buck, who played a key role in carrying out the groundwork that shaped the content of this handbook. Early in the project, she organized focus groups and conducted phone interviews with scientists who are leaders in agricultural systems research, many of whom reviewed the final product. Louise also contributed substantially to chapter 2.

I am thankful to the many people who served as sounding boards and who reviewed individual chapters or the entire manuscript at various points in the process, including Jill Auburn, Michel Cavigelli, Doug Constance, Nancy Creamer, Heather Karsten, Laura Lengnick, Mark Lipson, Marla McIntosh, Michelle Miller, Stephen Mirsky, Paul Mueller, Sieglinde Snapp, John Teasdale and Kathleen Yeater. I appreciate their useful comments. The book would not be what it is without the editors: I wish to thank Dave Malakoff as well as the countless past and present SARE Outreach staff for their editorial roles, including Valerie Berton, Andy Clark, Diana Friedman, Kim Kroll, Dena Leibman, Abigail Massey, Sean McGovern, Rachel Patterson, Mandy Rodrigues and Andy Zieminski. In particular, I want to acknowledge the contributions of Diana Friedman for shaping the introduction and chapter 1 so that interdisciplinary agricultural systems research is clearly linked to the SARE mission.

I am extremely grateful to the many farmers who have been generous with their time, contributing to my research and helping me to truly understand farming. They include Brian Caldwell, Jean-Paul Courtens, Jim Durst, Lou Johns, Lou Lego, Klaas Martins, and Ann and Eric Nordell. Lastly, I want to acknowledge and thank those colleagues whose ideas and insights have influenced my understanding of agricultural and ecological research: Deborah Letourneau, Mark Lipson, Chuck Mohler, Sieglinde Snapp, Ariena van Bruggen and Michelle Wander.

Laurie Drinkwater
June 2016

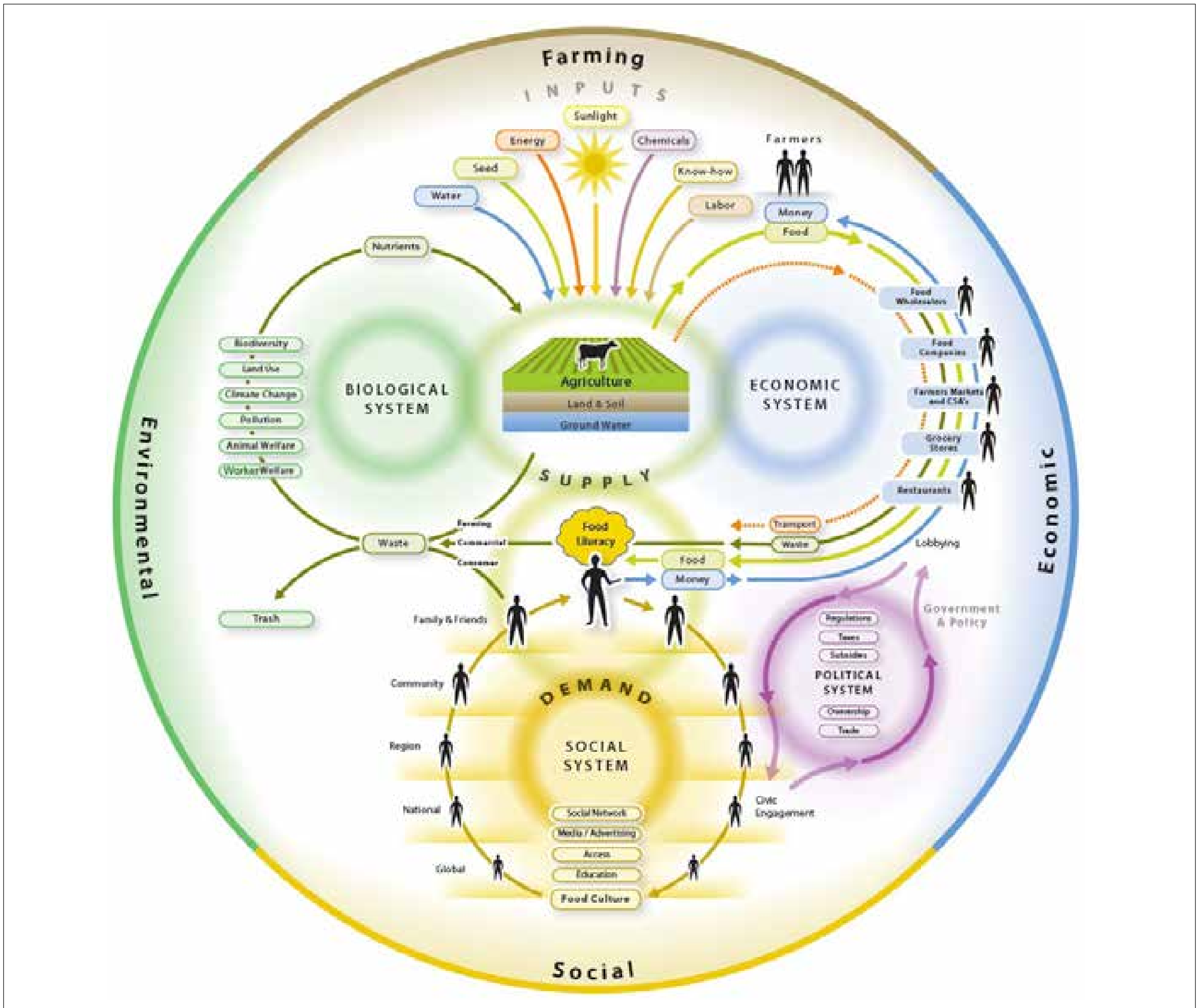
Introduction

We can't solve problems by using the same kind of thinking as when we created them.
—Albert Einstein

Agriculture in the United States is undergoing rapid transformation. Alongside production and economic pressures, farmers face a complicated suite of environmental goals such as protecting water and air resources, reducing agrochemical use, mitigating greenhouse gases and conserving biodiversity. In addition, many troublesome issues are directly linked to the dominant agricultural production system, including agrichemical runoff leading to dead zones and drinking water contamination, aquifer depletion, widely variable farm income, and loss of biodiversity.

To address these problems and also to create productive agricultural systems that protect the environment, provide sustainable income for farmers and help maintain healthy rural communities, agricultural research must be able to generate information that improves the whole farming

FIGURE I.1. Nourish Food System Map (WorldLink, 2014)



A Whole-Farm System viewpoint incorporates all of the environmental and socioeconomic aspects of a farm, including the larger environmental and socioeconomic context in which it is embedded.

system. Agricultural research must shift from measuring farm "performance" by single indicators such as yield and profit, to evaluating success using a multidimensional approach that incorporates the three dimensions of sustainability: environmental, social and economic.

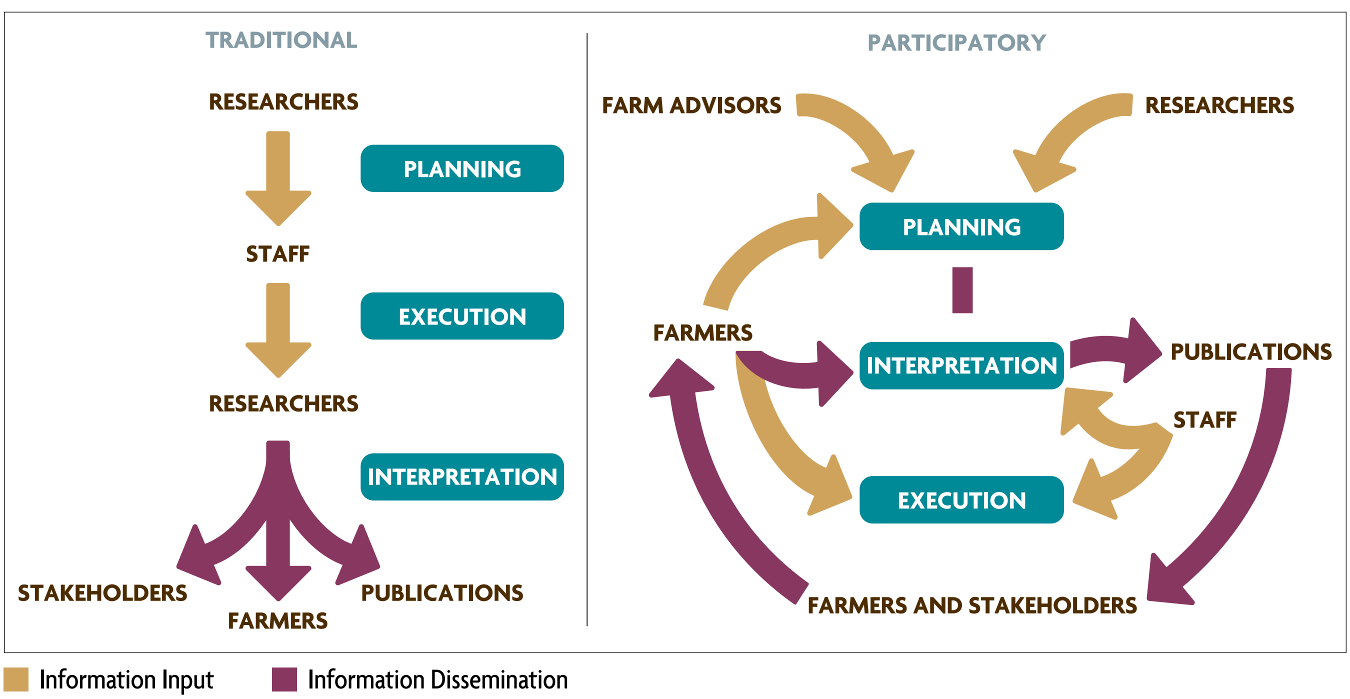
Systems research, holistic in nature and comprehensive in scope, is one such approach that can contribute to the development of agricultural systems that are environmentally, economically and socially viable while meeting production needs and addressing these systemic problems.

Systems research offers many benefits for agriculture and for society as a whole. By analyzing the complex interactions between farming practices and environmental and societal impacts, systems research can provide solutions and alternatives to these very problems while helping farmers maintain a sustainable livelihood. A systems approach also reaches beyond the individual field or farm to encompass the broader economy and environment, such as a rural community, watershed or county. Figure I.1 shows one model of an agricultural system. The graphic shows the components that comprise a food system, and the connections and relationships among those components. (See Chase and Grubinger [2014] for other viewpoints on agricultural and food systems.)

Because systems research can explore the mechanisms of entire agricultural systems, it frequently involves a diverse array of stakeholders such as producers, consumers, federal, state and local agencies, and extension agents. By integrating the expertise of these stakeholders, systems research teams can develop solutions that are applicable to real-world situations, and this approach often provides a wider range of innovative solutions compared to a single-discipline approach. Outside of research institutions, farmers continuously develop novel management systems that they share through farmer networks. By incorporating this wider knowledge base into the research process, participants learn from one another at all stages (Figure I.2).

Finally, systems approaches require that researchers from a variety of fields collaborate in designing and carrying out the research. Biological and environmental researchers join with sociological, political and economic experts to address factors such as the markets, laws and regulations that influence farmers' decision-making processes. For example, much research on environmental concerns such as water contamination, soil degradation or loss of biodiversi-

FIGURE I.2. Traditional Versus Participatory Information Transfer



ty has been conducted by biophysical and social scientists working separately. Solutions from biophysical scientists might emphasize changes in production practices, which often have limited success because they fail to account for socioeconomic factors. Likewise, policies based primarily on maximizing economic efficiency often do not reflect the environmental and climatic variability that farmers must respond to in managing their production systems.

Using a systems approach, researchers from these different disciplines join together to incorporate agronomic, ecological, economic and sociological theory. In doing so, they can develop a better understanding of how people make decisions and take action, and of how those actions affect yields, farm economics and the broader environmental, social and food systems.

Switching from single-outcome, reductionist research to systems research is not a simple proposition. This kind of shift involves major modifications of experimental designs and research protocols. Effective implementation of systems research requires researchers to take a different perspective on and approach to agricultural systems, scientific collaboration and experimental design, embracing substantial team effort and a crossing of disciplines, both of which are not the norms in university and research environments. Systems research also requires a significant time commitment, both in the short and long term. And finally, implementing a systems approach requires addressing institutional barriers, such as the lack of long-term funding for research and the promotion and tenure requirements for junior faculty.

However, as American agriculture continues to embrace sustainability, many of these barriers are shrinking. Practices that were considered fringe or alternative toward the end of the 20th century, such as cover cropping, integrated pest management and crop rotation, have been readily adopted by mainstream farmers. Market forces, such as those driven by consumer interest in organic and local foods, have become a main force in promoting farmer adoption of these and many other practices that emphasize sustainability. In response to widespread adoption of these approaches, many institutional research programs at the EPA and USDA now routinely incorporate sustainability and interdisciplinary systems approaches into their funding requirements. These programs, including the Organic Agriculture Research and Extension Initiative Program, the Organic Transitions Program, the Agriculture Food and Research Initiative, the Specialty Crop Research Initiative, the Agricultural Research Service and the Natural Resources Conservation Service provide further support for moving American agriculture toward more sustainable systems and the application of systems research (National Research Council, 2010). In its report *Toward Sustainable Agricultural Systems in the 21st Century*, the National Research Council (2010) calls for a transformative systems approach to modern agriculture, based on a systems approach, that involves integrating various research and extension disciplines and directing research toward innovative production systems that embody the goals of sustainability.

While not all scientific investigations can or should be conducted as large-scale, cross-disciplinary systems projects, even scientists whose research is narrower in scope can benefit from bringing a systems perspective to their work. Any line of inquiry is enhanced when researchers give thought to how their work fits into the larger context of agriculture, the environment and society.

As farmers continue down the path toward sustainability, as researchers incorporate systems thinking and approaches, and as the consumer-driven market presses for cleaner and healthier agriculture, systems research will continue to move to the forefront of the research agenda and help to develop new and vibrant systems for all of American agriculture. It is our hope that this book will contribute to that movement and discussion.

About *Systems Research for Agriculture*

This handbook is organized into five chapters that provide an overview of the theoretical underpinnings and history of systems research, give concrete examples of existing systems research projects, and offer detailed practical guidance on how to organize and execute a collaborative systems project. Each chapter includes a case study that highlights key facets of a systems research approach. An extensive list of recommended resources for each chapter can be found at the back of the book on p. 87–91.

Chapter 1, *Introduction to Agricultural Systems and Agricultural Systems Research: A Paradigm Change*, defines agricultural systems for the purpose of systems research, compares systems research with reductionist research methods, briefly describes the background and theory of agroecological and agricultural systems research, and provides concrete examples for shifting to a systems research paradigm.

Chapter 2, *Collaboration, Decision Making and Organizational Structure for Agricultural Systems Research*, provides guidance on how to develop leadership, teamwork and collaboration, build an interdisciplinary research team, instill a culture of collaboration, engage farmers and other nonacademic stakeholders in the research process, be an effective facilitator, conduct productive meetings, and manage inevitable tensions and disagreements.

Chapter 3, *Planning Interdisciplinary Agricultural Systems Research*, focuses on the process of planning a systems research project, including goal setting, hypothesis development, experimental design, site selection, statistical method considerations, and financial planning.

Chapter 4, *Analyzing the Performance and Sustainability of Agricultural Systems*, considers methods for managing complex data sets generated by systems projects, including statistical and mathematical tools (univariate and multivariate analyses and mathematical modeling), natural resource accounting methods (life cycle assessments, ecological footprints and carbon footprints), and sustainability indicators.

Chapter 5, *Implementing a Systems Research Project: Troubleshooting and Putting It All Together*, assembles the remaining pieces, with an emphasis on moving a project from startup to final publication, and provides a roadmap for developing and confirming plans, dealing with budget and accountability issues, and building flexible, resilient organizational structures.

References

Chase, L., and V. Grubinger. 2014. *Food, Farms and Community*. University of New Hampshire Press: Durham, NH.

National Research Council. 2010. *Toward Sustainable Agricultural Systems in the 21st Century*. The National Academies Press: Washington, DC.

WorldLink. 2014. Nourish Food System Map. www.nourishlife.org. All rights reserved.

1

CHAPTER 1

Introduction to Agricultural Systems and Agricultural Systems Research: A Paradigm Change

When we try to pick out anything by itself, we find it hitched to everything else in the universe.
—John Muir

Understanding Agricultural Systems

Agricultural systems can be described in many ways. Over the years, researchers and farmers alike have used a variety of terms, such as farming system, cropping system, organic, ecological, to identify agricultural systems based on particular characteristics or definitions. Many of these common terms are outlined in Box 1.1 (p. 12). In addition to these terms, which focus on unique sets of practices, management techniques, and sometimes philosophies, other definitions (e.g., a corn–soybean system, a vegetable or hog production system) focus on the commodity being produced. For the purposes of this handbook, we will use the term agricultural system to refer broadly to any system that produces livestock and crops (food, feed, fiber and/or energy), including the social, political and economic components of that system.

When appropriate, case studies or examples that fit into the categories in Box 1.1 will be identified, but agricultural systems researchers should not feel bound by these definitions when conceptualizing their own systems for research and educational purposes. Rather, they should pick and choose from each to best develop or delineate their own systems.

Key Concepts of Agricultural Systems

Drawing from general systems theory and ecosystem ecology, the following concepts provide the foundation for agroecology and are essential for conceptualizing and understanding agricultural systems for research purposes (Drinkwater, 2009). Taken together, they also provide a framework for facilitating interdisciplinary research.

1. Agricultural Systems are Defined by Unique Spatial and Temporal Boundaries

Agricultural system boundaries can be fixed, as is the case with a farm, for example, but systems can also be defined using subjective boundaries. In agricultural systems research, spatial and temporal boundaries are determined by research goals, the structure of the underlying environment, socioeconomic and political structures and by land-use decisions made by farmers and farm communities. For this reason, after the research question(s) or hypothesis is developed, the first step in delineating the system under study is to identify the physical and temporal boundaries that align with the problem being addressed. In a watershed study, for example, an experiment designed to measure the impact of spring tillage and planting on water quality could have a short-term focus. If the emphasis were to quantify nutrient loads leaving the watershed, then a multiyear study would be needed to reflect seasonal and year-to-year variability. Physical boundaries for a system vary widely, from a field or management unit or the property line for a specific farm (Shreck et al., 2006), to a collection of farms, an entire watershed (Strock et al., 2005) or a county.

2. Agricultural Systems are Composed of Interacting Subsystems

All systems are composed of many smaller, interacting subsystems that interact in either a hierarchical or nonhierarchical manner. The predominance of nested hierarchies of subsystems within agricultural and ecological systems is a striking feature. Watersheds are a prime example of a system composed of a nested hierarchy of subsystems. A large river basin, for instance, includes many smaller tributaries draining smaller watersheds, each of which has its own smaller system of tributaries and watersheds. Nested hierarchies are not always smaller versions of a larger system, as is the case with watersheds. More commonly, agricultural systems are composed of subsystems that have their own unique properties. For instance, fields may be aggregated into farms, and farms into watersheds, agricultural regions or counties (Strock et al., 2005; Gentry et al., 2009). In other words, each level in the nested hierarchy is composed of smaller systems that are distinctly different from the larger system. Alternatively, subsystems can also exhibit non-hierarchical relationships as seen in an integrated farm that produces grains and animals. In this case, the two enterprises are simply interacting subsystems within the larger farming system and are connected by exchanges of crop outputs (grain and forages for animal feed) and nutrients (manure applied to fields).

3. System Processes Occur at Different Scales and Rates

Just as system boundaries have unique physical and temporal boundaries, system *processes* also vary in space and time. For example, processes such as nutrient cycling occur at scales from a few microns to a whole plant, and from a single field to a farming community. Similarly, time-based processes can range from minutes to centuries; decomposition of labile organic matter, or population changes in pests due to predator–prey interactions, can occur within a single growing season (Letourneau, 1997; Puget et al., 2000). In contrast, detectable changes in stabilized soil organic matter or the emergence of weed resistance to herbicides can take years or decades to manifest (Aref and Wander, 1997; Vidal et al., 2007). During major shifts in management regimes, such as the transition from conventional to organic management or from conventional tillage to no-tillage, the rate of change for certain processes can be rapid, while other processes are not detectable for years or decades. For example, replacing fallow with cover crops can affect soil decomposers long before changes in total soil organic carbon can be detected. Because different processes will not reach dynamic steady-state conditions at the same time, the time frame of these various processes needs to be considered when planning research, particularly when focusing on the transition from one management system to another, because legacy effects from the previous system can interact with newly imposed practices.

4. System Structure Determines Function

In agroecosystems, structural properties (e.g., soil type, climate, biodiversity) drive functions such as plant productivity, nitrogen retention or greenhouse gas emissions, as well as emergent properties such as stability and resilience. This relationship between structure and function provides a useful framework for designing agricultural systems to optimize particular functions or for understanding the basis for differences across agroecosystems. For example, greater biodiversity in natural ecosystems often corresponds with greater productivity and enhanced resilience of the system. Thus, intentional management of species diversity can be a key strategy for achieving sustainable farming systems (Jackson et al., 2007).

5. Agricultural Systems are Open Systems

Agricultural systems are open, meaning that energy, nutrients, organisms and information constantly cross system boundaries. Quantification of net flows among system components and into and out of systems, such as nutrient and energy budgets, mass balance calculations and life-cycle analysis, is important for understanding the movements and effects of these processes and properties. For example, quantification of nutrient flow across a predefined system boundary such as a field or watershed is essential to understanding the impact of farm management on long-term soil fertility and on the surrounding landscape.

6. Agricultural Systems Have Emergent Properties
All systems have emergent properties, or characteristics and behaviors that are only apparent at higher levels of system complexity (von Bertalanffy, 1968). In other words, these properties only emerge when the system is operating as a complex of subsystems; emergent properties do not exist when the subsystems or components are observed in isolation. For example, animal organ systems, such as the digestive, reproductive and cardiovascular systems, exist as such but are not viable in isolation; however, when combined in an animal structure, the emergent property of life becomes apparent. In agricultural systems, soil quality can be considered an emergent property because it exists only as a function of the interactions among soil biological, physical and chemical processes (Carter et al., 2004). Sustainability is also considered an emergent property, because it emerges from the multiple social and physical interactions within the system (Chase and Grubinger, 2014; Lengnick, 2015).

Understanding Systems Research

With these key concepts as the foundation, the goal of systems research is to develop knowledge about how a complex system functions as a whole. This goal, with the assumption that the interactions among components must be studied in order to understand the whole system, is the hallmark of systems thinking. Hence, agricultural systems research strives to develop knowledge about (1) how an agricultural system is influenced by the relationships among its component parts and (2) how that complex system functions as a whole.

From Reductionist Research to Systems Theory: Getting from There to Here

Unlike reductionist research, systems research strives to provide an understanding of how complex systems function as a whole and presumes that (1) a complex system is characterized by nonlinear interactions among its components, and that (2) these interactions create the feedbacks that are the basis for the self-regulatory and emergent qualities of complex systems. In other words, any complex system is more than the sum of its parts. This approach differs from the guiding assumptions of reductionist science, which are that (1) systems can be broken down into their individual components and analyzed as independent entities, and (2) components can be added together in a linear fashion to describe the total system.

> "Systems thinking" is a useful approach to organizing information in ways to help understand the complex systems that make up our world.

While reductionist science has a place in the research toolbox, systems-based research, and specifically interdisciplinary systems research (discussed further in chapter 2), provides an additional tool for better understanding real-world complexity while emphasizing the connections between production systems and the associated environmental and social systems.

The roots of agricultural systems research can be traced back to the 1800s, when the first long-term crop rotation studies were established to compare distinct cropping systems. In the United States, most of these early experiments, such as the Morrow Plots (established in 1876 at the University of Illinois, Urbana-Champaign) and Sanborn Field (established in 1888 at the University of Missouri), were initiated to compare simplified rotations with traditional, complex rotations using animal and green manures.

As research shifted in the 1940s to management strategies such as soluble fertilizers, herbicides and pesticides that were effective in much shorter time frames, and therefore could be studied using reductionist methods, cropping systems research fell out of favor.

However, farming systems research, which focuses on economic goals as well as production systems, arose in international development circles during the 1970s as a strategy to help limited-resource farmers improve production technologies (Shaner, 1982). This approach garnered attention from international agriculture and rural development organizations for its promise to overcome the limitations of conventional agricultural research, which was oriented exclusively toward supporting national production and development goals without regard to their effects on rural producers and consumers. For the first time, research teams that included agronomists, economists and farmers began to study working farms. By the late 1980s, this type of research had become institutionalized in national and

BOX 1.1. Nomenclature for Agricultural Systems

Over time and throughout the literature, agricultural systems have generally been defined by philosophy or management practices. For example, a farming system is defined as "the manner in which a particular set of farm resources is assembled within its environment...for the production of primary agricultural products...a unique and reasonably stable arrangement of farming enterprises that a household manages according to well-defined practices in response to the physical, biological, and socioeconomic environment and resources." (IRRI, 2012).

Definitions of some major types of farming systems in common use by agricultural researchers, policymakers and farmers follow.

Conservation agriculture systems employ resource-conserving methods but are also considered high-output agricultural systems. Conservation farming typically involves the integrated use of minimal tillage, cover crops and crop rotations.

Reduced- or low-input farming systems minimize the use of off-farm resources such as commercially purchased chemicals and fuels. These systems also tighten nutrient and energy cycles and use internal resources such as biological pest controls, solar or wind energy, biologically fixed nitrogen, and other nutrients from green manures, organic matter or soil reserves. Many reduced- or low-input farming systems are examples of integrated farming systems.

Integrated farming systems combine methods of conventional and organic production systems in an attempt to balance environmental quality and economic profit. For example, integrated farmers build their soils with composts and green manure crops but also use some synthetic fertilizers in addition to biological, cultural and mechanical pest control practices.

Alternative livestock production systems use lower-confinement housing and rely more on pastures than do conventional and industrial livestock farms. A common example in dairy farming is the use of intensive rotational grazing practices in which short-duration, intensive grazing episodes are followed by long rest periods that allow pastures or fields to recover.

Integrated crop–livestock farming systems generate a significant fraction of animal feed on cropland and pastures owned or managed by the livestock farmer. These systems use the crop and livestock enterprises to efficiently recycle nutrients, promote crop rotations and insulate livestock farmers from price fluctuations in feed and input markets.

Organic agriculture is both an ecological production management system and a labeling term that indicates that the food or other agricultural product has been produced using approved methods that integrate cultural, biological and mechanical practices that foster cycling of resources, promote ecological balance and conserve biodiversity. Synthetic fertilizers, sewage sludge, irradiation and genetic engineering may not be used.

Ecologically based farming systems emphasize the use of ecological pest management, nutrient cycling, and natural and renewable resources to enhance soil health and protect water quality. Organic and other "natural" farming systems fall under this category, relying on many common practices such as crop rotations, biological pest control, manures and avoiding all or most synthetic fertilizers and pest controls.

Food systems refer to a complex set of activities and institutions that link food production to food consumption. Food system studies often use a "commodity chain" approach to analyze production, processing, selling and consumption.

(Adapted from National Research Council, 2010) international agriculture research organizations worldwide (Baker and Norman, 1990).

In the United States, interest in whole-systems research was revived in the 1980s, largely as a result of the sustainable agriculture movement. Much of the early research around sustainability drew from the international farming system movement. The Farming Systems Trial at the Rodale Institute was the earliest of these second-generation cropping system experiments in the United States (Liebhardt et al., 1989; Peterson et al., 1999). This long-term trial influenced numerous cropping systems experiments established in the United States during the 1980s and 1990s. Early examples funded by SARE include the Sustainable Agriculture Farming Systems (SAFS) Project in Davis, California, (see p. 35), the Research Unit at the Center for Environmental Farming Systems (CEFS) in Goldsboro, North Carolina (see p. 20), studies on forage and livestock systems in High Plains agriculture in Texas, and a study on transitioning from conventional to organic agriculture in West Virginia. More recent examples of SARE-funded systems projects include the development of sustainable cropping systems for dairy operations at Penn State and a fully integrated, self-sustaining dairy farm at the University of New Hampshire (see p. 76).

At the same time, ecologists were beginning to apply ideas about ecosystems to agriculture, eventually giving rise to the concept of "agroecosystems" and a new conceptual framework for studying agricultural systems known as agroecology (Gliessman, 2014). By providing a solid theoretical and conceptual base, agroecology has played a huge role in the development of whole-systems thinking in agriculture (Gliessman, 2014). Much of the theory and many of the ideas presented in this handbook are derived from agroecology and agroecosystem-based research.

While systems-based research cannot replace reductionist science, it can provide an additional tool to better understand the complexity of the real world while emphasizing the connections between production systems and the associated environmental and social systems.

Changing Paradigms for Agricultural Research

Moving from a reductionist approach to a systems approach is a complex process that involves more than minor modifications to experimental designs or research protocols. Effective implementation of systems research requires thinking and acting in entirely different ways about agriculture and agricultural systems, scientific collaboration and experimental design.

This shift can be loosely divided into the following three areas:

Rethink. Researchers must move from concentrating on individual components and simplistic cause-and-effect relationships, to a holistic view that encompasses all parts of the system and the interconnectedness among those parts. In other words, researchers must think in terms of whole systems when defining the system under study.

Redesign. Researchers must overhaul the way in which they design agricultural research as they move from factorial to systems approaches.

Regroup. Collaboration is essential. Because real-world agronomic problems rarely occur within disciplinary boundaries, teams of scientists and agricultural practitioners who are familiar with different parts of the system and who can share their expert knowledge must work together to accomplish problem solving. In many large-scale systems research projects, particularly those funded by SARE, farmers are at the research table from day one, providing input and suggestions for design and implementation.

Rethinking the Experimental Approach

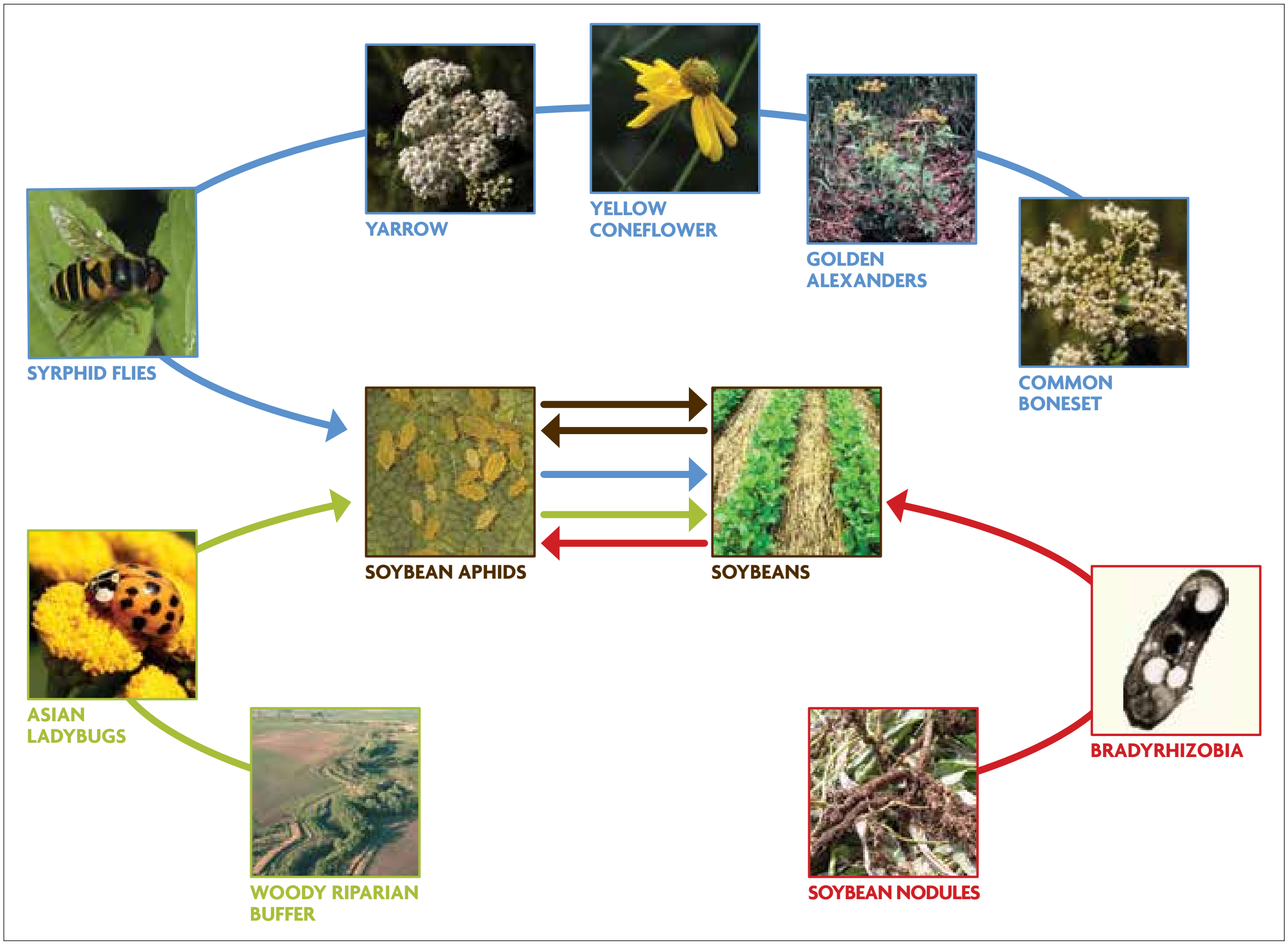
The move away from a focus on individual parts and cause–effect relationships to a holistic view is critical to applying a systems approach. A good first step is to develop a conceptual model or map of the components and interactions that make up the system of interest. Such models can be very useful in developing the research questions and hypotheses. For example, consider the following case study that contrasts reductionist and systems approaches to management of the soybean aphid.

Researchers following a conventional reductionist approach would likely address an aphid problem by asking, "How can the soybean aphid be controlled?" They might then design a short-term factorial experiment to test specific practices, such as varying rates and types of pesticides, working from a reductionist position that soybean aphid dynamics are independent of other factors in the agricultural environment.

Researchers using a systems-based approach would begin differently, perhaps by framing the question in broader terms by asking, "What interactions and processes within the agricultural system regulate/impact soybean aphid populations and life cycle?" Because so many possibilities exist, a practical next step might be to represent the options graphically using illustrations or a concept map.

Figure 1.1 is an example of a concept map that could be used by a collaborative research team; the map shows processes and interactions that could affect soybean aphid

FIGURE 1.1. A Systems Approach to Controlling Soybean Aphids



Concept map of ecological mechanisms that could be used to manage soybean aphids in corn–soybean systems in the Midwest. Photo credits (from bottom left): Lynn Betts, Natural Resources Conservation Service; David Cappaert, Michigan State University, Bugwood.org #2107002; David W. Ragsdale, Texas A&M University, Bugwood.org #1460039; Susan Ellis, Bugwood.org #1366018; Theodore Webster, USDA Agricultural Research Service, Bugwood.org #1553273; Rob Routledge, Sault College, Bugwood.org #5498704; Larry Allain, Natural Resources Conservation Service; Ohio State Weed Lab, The Ohio State University, Bugwood.org #1554169; courtesy of SARE; courtesy of Timothy R. McDermott.

populations in a Midwest corn–soybean system. The red arrow indicates naturally occurring strains of bradyrhizobia, nitrogen-fixing bacteria that inhabit soybean nodules and that confer resistance to soybean aphids (Dean et al., 2009). The blue arrows point to native plant species that provide habitat for syrphid flies, a natural enemy of soybean aphids (Rutledge et al., 2004). The green arrows indicate the Asian ladybug, also a natural enemy of aphids. Asian ladybugs overwinter in trees and tend to be abundant in regions with woody buffers (Gardiner et al., 2009).

This concept map allows researchers to view known interactions that could contribute to aphid control, thus helping them shape the direction of their research. This example demonstrates that systems research entails painting a more expansive and interconnected picture than traditional reductionist methods. It also suggests that a systems approach to research and management of soybean aphids (and other insect pests) involves the use of multiple strategies rather than a single, "silver bullet" solution. (See chapter 2 for more information on the use of concept maps.)

Redesign

The most commonly used approach in standard agricultural research is the factorial design. In a factorial design, researchers simultaneously study the effects of two or more factors at two or more levels, usually by comparing various combinations (Little and Hills, 1978), while holding all other attributes constant. This design allows investigators to

BOX 1.2. Challenges of Reductionist Design

Researchers using factorial designs face a number of challenges, one of which is the fundamental assumption that experiments accurately simulate the agricultural system under study. In many instances, experimental designs aimed at isolating specific processes or factors result in oversimplification; in an effort to hold all variables constant except for those being tested, investigators change—or even completely eliminate—key interactions among parts of the system. For example, when researchers test organic farming systems by varying one factor in isolation—such as by comparing plots that have been sprayed with herbicides to plots with mechanical weed cultivation—the organic systems may not appear to perform as well as conventional growing systems because management history has changed the background conditions (e.g., soil properties and weed populations), and specific adjustments (e.g., to rotation, tillage, planting date) must be made to compensate for the absence of chemical weed controls. To study organic farming systems properly, a systems-based experimental design that includes all of these parts must be used.

Factorial designs can also lead to the use of experimental plots in which management practices do not reflect a realistic production system. To minimize variation across treatments, factorial design dictates that all management practices other than experimental factors remain the same for all treatments. In the real world, however, farm management systems are interconnected and a change in one practice usually means that other components must be modified. For example, changes in tillage often necessitate shifts in planting date or crop variety. Such shifts contribute to the challenges of using factorial designs and highlight another advantage of systems-based research: it is generally more compatible with the way real farmers approach management and problem solving.

deconstruct a complex system, isolate specific components and identify cause-and-effect relationships about production questions. For example, a factorial design approach could be used to ask, “How do specific tomato varieties respond to varying rates of organic or inorganic fertilizer?” This research would evaluate the response of each tomato variety to organic and inorganic fertilizer rates in isolation of other factors.

However, in reality, tomato plants respond to many factors other than the type or rate of fertilizer, such as soil structure, moisture and pest pressure. Because factorial designs do not simulate a system, but instead isolate specific processes or factors, they often result in oversimplification. In an effort to hold all variables constant except for the factors being tested, investigators change or even eliminate key interactions among parts of the system (Drinkwater, 2002) (see Box 1.2).

A common mistake in many early agricultural systems research projects was to apply this factorial approach to new systems under development. This led to poor results, because the experimental design simply represented a modified reductionist approach (Janke et al., 1991). Rather than redesigning the system to include the many factors that are essential to the success of a sustainable system—soil health, microbial diversity, cover crops, economic price advantages and so on—researchers simply removed and/or substituted one factor at a time, such as herbicides or pesticides. To truly test an entire system, the design must allow each management regime or treatment to perform optimally, even if this means widening the variability in production practices and experimental design.

An excellent example of design that mimics a system, rather than substituting practices, is the Sustainable Agriculture Farming Systems (SAFS) experiment in Davis, California. A SARE-funded project that ran for many years, SAFS (see p. 35) was a long-term trial that compared conventional and cover cropped tomato rotations. Early in the experiment, farmer cooperators pointed out that the cover cropped system was performing poorly because it was planted late due to the need to plow down fertility-providing cover crops. So the research team made an adjustment: they modified the system to fit typical best farming practices in the area by switching to tomato transplants in the cover crop system, rather than mimicking the conventional system. This meant the cover cropped system had a later planting date, used different varieties and had a completely different irrigation schedule. After these modifications were made, the cover cropped system became not only economically competitive, but also more efficient in terms of energy and water use. Had the researchers held planting dates and varieties constant between the two systems, the cover cropped system would likely never have been economically competitive and its potential performance would have been severely underestimated.

This example also points to the need for longer time frames to reap the full benefits of agricultural systems research. First, researchers need time to gain experience and to adjust the experimental design, even if they have had early input from farmers. Second, short-term experiments that typically last only two to three years provide little opportunity to analyze ecological processes that may take many years to manifest. For example, soil nutrient availability is influenced by soil management history, and many soil processes require far more than one or two growing seasons to approach a steady state. Specifically, nitrogen availability is determined by a combination of very rapid processes, such as microbial biomass turnover, and slower processes that regulate the quantity and composition of soil organic matter (SOM). As a result, when soil treatments such as no-till are introduced after decades of conventional tillage, changes in nitrogen and carbon cycling can reduce plant-available nitrogen for the first few years (Meisinger et al., 1985). This effect declines over time, however, as SOM reaches a new steady state. Similarly, shifting from inorganic nitrogen fertilizers to organic amendments such as compost or green manures also initially reduces nitrogen availability, which then increases gradually as soil-cycling processes reach a new steady state (Liebhardt et al., 1989; Clark et al., 1999). If trials are designed to reflect only short-term effects such as yield response, they cannot accurately measure the effects of biological processes that take considerably longer to manifest.

Systems research redesign also means that larger study sites or plots than those typically used in standard reductionist research trials are required. Landscape characteristics at scales larger than common experiment station plots have been shown to influence experimental outcomes such as crop damage (Letourneau, 1997) and pest abundance, suggesting that in some cases, it may be necessary to move beyond the experiment station to include surrounding areas in the research. For example, large-scale research has shown a link between landscape-level vegetation and the populations, diversity and behavior of beneficial insects, including natural enemies such as parasitoids. In a study by Marino and Landis (1996), the diversity of landscape-level, not field-scale, vegetation determined the effectiveness of parasitoids on armyworm larval stages in maize fields. Although parasitoid species diversity was similar at both landscape scales, mean percentage parasitism was significantly higher in fields situated in a complex landscape compared to fields surrounded by a simple landscape (13.1 percent versus 2.4 percent). Such findings suggest that replicated factorial experiments conducted in small plots at single locations are not always adequate for evaluating the efficacy of biological pest control practices.

Systems redesign presents a particular challenge in that not only must each system be defined and evaluated differently (see chapters 3 and 4), systems studies also generally include a variety of experimental designs and often use multiple strategies within a project. These strategies can include on-farm and participatory research, case studies, surveys and interviews, focus groups, landscape-level data collection and differing management regimes.

Finally, while systems-based research emphasizes the study of multiple components and their interactions, it does not preclude the use of tools that are also used in reductionist approaches, such as replication, factorial design and statistical analysis. Controlled experiments that can identify cause-and-effect relationships and pinpoint underlying mechanisms are useful for solving complex problems within a systems context. For example, studies of long-term farming systems often use a randomized complete-block design with a cropping system as the main treatment (Liebhardt et al., 1989). Smaller, short-term factorial experiments are frequently used as "satellite trials" to test specific practices to be incorporated into larger cropping systems experiments. Investigators also embed smaller replicated plots, sometimes with factorial treatments, in farm fields or large experiments (Kramer et al., 2002; Schipanski et al., 2010). All of these approaches are discussed in more detail in chapters 3 and 4.

Regrouping

By its very nature, systems research is most effective when conducted collaboratively by multi- or interdisciplinary teams that have a large body of collective knowledge. In the example of the soybean aphid (p. 14), the research team pursuing a systems approach would have needed, at a minimum, experts in entomology, plant pathology and soil biology. As problems and the questions developed to address them become more complex, the composition of the team must become more diverse.

Nitrogen loss is an example of a phenomenon or process that can be best understood from a systems perspective using a team with diverse areas of expertise. At the biophysical level, nitrogen loss depends in large part on the amount, timing and type of fertilizer a farmer applies to a field, and much research has focused on optimizing these management factors. However, the farmer's application rate is not only based on these management considerations but is also influenced by environmental and social factors including soil conditions, crop rotation, government policies, private markets and the farmer's views about the costs and benefits of fertilizer. Furthermore, once the fertilizer is applied, a wide range of environmental processes such as rainfall patterns and bacterial nitrogen transformations continue to affect the rate of nutrient loss.

From this brief summary, it should be clear why a diverse team is essential to approaching agricultural research from a systems perspective. Agronomists are needed to focus on improving fertilizer use efficiency. Soil nutrient management specialists would research improved fertilizer application methods that enable crops to use a greater proportion of applied nutrients. Extension educators would communicate information about best management practices to farmers. Plant physiologists and molecular geneticists could tackle crop improvement, including the development of crop varieties that use nitrogen more efficiently. Experts in water management and hydrology would explore engineered solutions, such as the construction of swales and wetlands to "soak up" excess nitrogen. Economists and other social scientists would be on board to evaluate human factors.

For example, in the Judith Basin in Montana, biophysical scientists proposed changing the type, amount and rate of fertilizer application to address a nitrate problem, but farmers were not interested in reducing fertilizer rates at the expense of yields. After conducting extensive surveys and interviews with the farmers, a team of sociologists identified the need to reframe the research away from a singular focus on nitrogen fertilizer management to a broader, systems-level effort aimed at acquiring more information on nitrate dynamics in the field and under different management systems. This shifted the emphasis away from identifying fertilizer as the problem to a much broader view of the crop and soil system, which made sense to the farmers. Working together, farmers and scientists reframed the research question and jointly interpreted the results, which showed that the intersection of crop rotation status, soil nitrate levels and rainfall patterns determined when and where nitrate pulses to groundwater were likely to occur. This approach provided a more complex picture of the issue and increased the likelihood that researchers could develop solutions that farmers were apt to use. (See Box 1.3 for other examples of how social scientists have played a key role in systems research projects.)

The importance of including sociologists, economists and other social scientists from the start and throughout the project cannot be overstated. Many of the current environmental problems in agriculture and the failure to produce results that translate into economic security for farmers stem directly from this lack of cross-disciplinary work.

Seeking to broaden their approach to understanding postharvest handling of fresh fruits and vegetables from farm to consumer, faculty from the Food Science and Agricultural Engineering departments, as part of the University of Georgia Postharvest Research Team, joined with an agricultural economist to develop a research plan that expanded beyond the physical and quality aspects of postharvest handling. Together, this interdisciplinary team expanded their reach to look at how postharvest handling affected price and to determine what price the market would bear. Had the team not included the economist from the start, it would not have been able to apply hedonic price modeling, i.e., to examine price factors resulting from both internal characteristics and external factors (Box 1.4).

Along with including multiple research disciplines, agricultural systems research also requires expansion beyond academia. Research is not created in a vacuum; it stems from and reflects current farming practices. Whereas traditional research paradigms have tended to assume a linear relationship with one-way flow—researchers develop innovations, extension workers recommend and spread them, and farmers adopt or reject them—in reality, interactions and knowledge flows among farmers, extension educators and researchers are multidirectional.

Because agricultural systems research is designed to incorporate multiple views and approaches, it widens the scope of who is considered an expert by valuing different ways of knowing, thus opening the research table to multiple stakeholders: extension, community groups, government agencies and farmers—the very practitioners who are the recipients of the research. Agricultural systems approaches can more easily involve farmers and other stakeholders at all stages of the research process—initiation, planning and implementation—and enable all participants to learn from each other. By improving the flow of information from the start, agricultural systems research also encourages new kinds of innovation. Chapter 2 discusses regrouping and collaborative team building.

The case study from the Center for Environmental Farming Systems in North Carolina demonstrates how multiple stakeholders can use all of these approaches—rethinking, redesigning and regrouping—to find new solutions to old problems.

BOX 1.3. Sociology In Systems Research

Eco-friendly, biodegradable alternatives to polyethylene plastic mulch have been available since the 1980s, but vegetable growers have long been reluctant to use them, even though they are cost-effective in the long term, require less labor and are more environmentally sustainable than plastic mulches.

To better understand this reluctance, a multidisciplinary team of researchers from Washington State University, the University of Tennessee, and Texas A&M University, with sociologists at the forefront, conducted focus groups and surveys with farmers and extension educators. The group found that farmers were disinclined to use biodegradable plastic mulches because of insufficient knowledge about the technology, high upfront costs, unpredictable breakdown in the soil, and unknown soil impacts.

The research, funded by a USDA-SCRI grant from 2009 to 2013, was the first of its kind: it applied sociological research to document the perceptions of vegetable farmers in order to determine barriers and bridges to using alternatives to polyethylene plastic mulch. With this information, the multidisciplinary team is now working beyond the typical field studies that test new mulch products and is working directly with farmers to find biodegradable mulches that will be effective. The team is developing an outreach strategy so that farmers have the opportunity to learn the ins and outs of using the new technology. In this example and in the Judith Basin nitrogen case mentioned on p. 17, the problem was approached at first from a purely environmental perspective, and without success. However, the inclusion of social scientists provided the opportunity for farmers' voices to be heard. By focusing on farmers as an integral part of the ecosystem and by determining what motivates their decision-making, social scientists enable a team to develop more applicable, lasting solutions. University of Vermont anthropologist Jason Parker notes that understanding the stakeholders in the system is integral when working with a specific community. "It's not about learning [a specific language] but learning how people speak and think about a particular issue or topic. If you can do that, then you are likely to be more successful collaborating with people to share a project's outcomes," says Parker.

Sociologists understand that the factors influencing farmers' decisions are complex and go beyond simple economic or environmental considerations. In fact, because farms are often run as a family unit, they are not traditional businesses, and therefore farmers are not traditional businessmen and women. Farmers make decisions based on influences at varying societal levels, including the following:

- Individual: farmer, family members, farmworkers
- Household: family resources and needs, land availability, farm succession
- Community: neighborhoods, community groups and organizations
- Institutional: state and government rules, regulations, policies, population's needs.

Sociologists interpret how farmers interact within these societal levels in the agricultural system. Involvement of a sociologist in a research project leads to a deeper understanding of the farmer's perspective, which may not be obvious to a biophysical scientist. According to Dr. Shoshanah Inwood, rural sociologist at the University of Vermont, sociologists recognize that farmers are diverse. They make decisions based on different drivers, values and experiences, meaning that similar systems research projects in different regions of the United States might yield totally different results. "When we talk about policy and programs, we can't assume that all farmers are going to be able to engage in the programs in the same way," she says.

In systems research that aims to address connections between society and production systems, a sociologist should be on the team from day one to help guide the development of the study to effectively explore societal influences on farm management decisions. SARE has found that having sociologists on planning teams is integral to advancing sustainable agriculture because of the critical role the sociologist can play in drawing connections across the biophysical and social divide. Each of SARE's four Administrative Councils, which help determine the grants that the program will fund each year, has a rural sociologist representative. This representative reviews research proposals to determine if they are asking appropriate questions that factor farmers' livelihoods into the research approach.

"Changing the food system and sustainability is a three-legged stool. We need crop scientists, we need animal scientists and we also need social scientists. In the long run, this will improve the quality of the food system in the United States," says Doug Constance, a sociologist and Southern SARE representative.

BOX 1.4. The Role of Economists in Systems Projects

Often, in typical cross-disciplinary projects, the following scenario occurs: A paper (or grant proposal) based on biophysical research is submitted for review. The research (or plan) is complete and the authors wait for the (hopefully) minor changes suggested by the reviewers. The review comes back and is generally favorable with the exception of one dreaded phrase: “This research is interesting but we suggest adding an economic component to the work.”

With that, the principal investigator (PI) looks at the list of faculty in the economics department to see if he or she knows anyone there. Failing that, a call to the department head connects the PI with an economist who might have some interest in the general area. After describing the project, the PI asks if the economist would be interested in working on it. When the economist asks when the project will start, the answer is that the project is actually over, and that “We just need a few budgets run to make sure our results make economic sense for the farmer.”

This is the typical way in which economists are involved in multidisciplinary projects—rarely at the beginning (usually at the end), with a request for some budget numbers to prove that the results obtained do not lower profits.

Not surprisingly, the PI is usually disappointed with the negative response he or she generally receives. After hearing that “running budgets” is not something economists do regularly as part of our research (getting budgets published is impossible), and being informed that, at best, perhaps a master’s student could help next semester after classes are finished, the PI is still baffled. Economics is budgets, isn’t it?

A lack of understanding of the science, as well as the social science, of economics often brings researchers from the physical disciplines and economists to a standstill. But consider an alternative scenario in which an interdisciplinary team is formed to explore an agricultural system. That system can be large (from farm to consumer) or it can be some subset that crosses boundaries in the production and distribution process. Given that the system involves multiple subsystems and components, it makes sense to look at how economic incentives affect decision-making.

From the beginning of the project, the interdisciplinary team includes an economist so that when plans are formed and a research protocol is established, the economic component of the system is included in the objectives and methods. Budgets may be a small part of the effort, but the project will address an important economic question that would not have been asked if the economist had not been involved at the outset.

Most important, the project design will include gathering economic data at the same time as other data, which will allow the economic component to fully match the physical aspects of the research.

The Postharvest Research Team at the University of Georgia operated in such a manner when investigating how fresh fruits and vegetables were handled from farm to consumer. We were careful to make sure that in each of our projects, all three researchers could identify a research product that would be publishable in journals within our disciplines as well as in interdisciplinary outlets. We shared coauthorship of all work (the author order depended on the publication) and planned all data gathering and analysis with the three disciplines in mind.

Successful interdisciplinary research is difficult; meetings are often time consuming, understanding the research needs of other disciplines can be challenging, and gathering all the necessary data can be expensive. Yet, there is no substitute for interdisciplinary research in order to fully understand systems and to perform insightful systems research. The most interesting and useful research I have done has been with colleagues in those other disciplines—and we never did a budget.

Jeff Jordan, Professor of Agricultural and Applied Economics
University of Georgia

SARE CASE STUDY | CEFS: Research Integrated Across Social, Economic and Biological Boundaries

Plots at the small-farm unit at CEFS. Photo courtesy of Andy Zieminski

The Center for Environmental Farming Systems (CEFS) in Goldsboro, North Carolina, thrives in large part because it represents a unique partnership between two land-grant universities and the North Carolina Department of Agriculture (NCDA). An outbreak of a noxious weed showed that these types of social relationships can be complex but that truly collaborative approaches can provide alternative paths not easily accessed in more traditional research settings.

In 2000, the discovery of tropical spiderwort at the Cherry Research Farm, where CEFS is located, alarmed local producers who insisted that the entire farm be fumigated. Officials from the NCDA, which owns the Cherry Research Farm and has a politically appointed leader, felt obliged to listen.

CEFS researchers, however, knew that fumigation would pose a major setback to their work, which included a number of long-standing, systems-based research projects focused on soil changes. As an alternative, they proposed keeping the weed in check by using a scouting program, adjusting crop rotations to discourage its growth and conducting inspections of equipment entering and leaving the farm. The approach worked, highlighting the value of working together to identify new solutions to old problems.

"Coming together to think through the science and politics to get to a rational solution that wouldn't ruin 10 years of research [was] a balancing act," says CEFS Director Nancy Creamer, a professor of horticultural science at North Carolina State University.

CEFS was established in 1994 after a task force of researchers, extension agents, producers, representatives from nongovernmental organizations and government officials determined that a facility dedicated to the long-term, large-scale study of sustainable and organic farming systems would strengthen the state's agriculture. Today, it has added programs in academics, marketing, local food systems and community outreach, creating the kind of vibrant multidisciplinary blend that is essential to systems-based research. Southern SARE has funded many of the research and outreach projects that have helped extend CEFS's impact and have allowed it to thrive.

"We've really broadened our focus and impact," Creamer says. "There's such momentum across the state in sustainable agriculture and local food systems that we're able to reach a broader audience than before. The involvement of state agency officials, county government, health officials, hunger advocates, conventional agriculture and sustainable agriculture nonprofits all working together in high-level management ensures that we reach a broad constituency."

The wide view also fits the institution's philosophy, adds Paul Mueller, an emeritus NC State crop scientist who was instrumental in the establishment of CEFS and who served as the first coordinator of the farming systems research unit. "CEFS has always been thought of as a facility for all three missions" of land-grant universities. "It represents a seamless crossover between extension, research and academics."

CEFS field research units focus on six research areas: alternative swine production, farming systems, organic systems, pasture-based beef, pasture-based dairy and small-farm production. These units reflect "major issues here, primarily in eastern North Carolina," says John O'Sullivan, who was head of the small-farm unit and was a codirector of CEFS until he retired in 2014 from North Carolina Agricultural and Technical State University.

Instead of traditional factorial designs, CEFS researchers use diverse management strategies in each of their production system treatments. For example, CEFS's farming systems research unit is involved in studies that compare five ecosystems. Three are agricultural production systems with distinct management strategies: an integrated crop-and-animal system, an organically managed cropping system and a conventional cash cropping system. The fourth is a successional ecosystem, and the fifth is a plantation forestry system.

CEFS coordinators say that one of the most important considerations in conducting long-term systems research is sustaining momentum by nesting smaller, shorter studies within bigger, longer projects. Such two- and three-year-long nested projects not only allow researchers to test questions that arise from the main research trials, they also help produce regular results, secure grant funding and involve graduate students. "There are not many of these kinds of [long-term] studies in existence, and there's a good reason for it," says Mueller. "It takes a long time to get results. You have to be patient enough to wait, and a lot of institutions and funding sources aren't patient."

Photo courtesy of Southern SARE

CEFS researchers have organized dozens of nested studies, which partly address these barriers. One, for instance, compared heritage turkeys with conventional broad-breasted turkeys raised on pasture. The research, which has helped many area farmers to introduce heritage birds onto their farms, has significant state-level implications: 20 percent of the turkeys sold in the United States in 2007 were raised in North Carolina.

Mueller says that the experience with tropical spiderwort, the noxious weed, illustrated the importance of another lesson in design: flexibility. Researchers in his farming systems unit, for instance, had to change some of the crops and planting rotations used in their five-system comparison studies after they discovered that some practices encouraged growth of the weed. The changes, however, did not compromise the overall integrity of the research, in large part because the five systems are very different, and the research is designed to be long term. The scale and variation, Mueller says, provides "some wiggle room if you need to make adjustments."

References

Aref, S., and M.M. Wander. 1997. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the Morrow Plots. *Advances in Agronomy* 62: 153–197.

Baker, D., and D. Norman. 1990. The Farming Systems Research and Extension Approach to Small Farmer Development. In *Agroecology and Small Farm Development*, ed. M. Altieri and S. Hecht. pp. 91–104. CRC Press: Boca Raton, FL.

Carter, M.R., S. Andrews, and L.E. Drinkwater. 2004. Systems Approaches for Improving Soil Quality. In *Managing Soil Quality-Challenges in Modern Agriculture*, ed. P. Schjonning, B.T. Christensen, and S. Elmholt. pp. 261–281. CAB International: Oxford, UK.

Chase, L., and V. Grubinger. 2014. *Food, Farms and Community*. University of New Hampshire Press: Durham, NH.

Clark, M.S., W.R. Horwath, C. Shennan, K.M. Scow, W.T. Lanini, and H. Ferris. 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. *Agriculture Ecosystems and Environment* 73: 257–270.

Dean, J.M., M.C. Mescher, and C.M. Demoraes. 2009. Plant-rhizobia mutualism influences aphid abundance on soybean. *Plant and Soil* 323(1): 187–196.

Drinkwater, L.E. 2002. Cropping systems research: reconsidering agricultural experimental approaches. *HortTechnology* 12(3): 355–361.

Drinkwater, L.E. 2009. Ecological Knowledge: Foundation for Sustainable Organic Agriculture. In *Ecology in Organic Farming Systems*, ed. C.A. Francis. American Society of Agronomy: Madison, WI.

Gardiner, M.M., D.A. Landis, C. Gratton, C.D. DiFonzo, M. O'Neal, J. M. Chacon, M.T. Wayo, N.P. Schmidt, E.E. Mueller, and G.E. Heimpel. 2009. Landscape diversity enhances biological control of an introduced crop pest in the north-central USA. *Ecological Applications* 19(1): 143–154.

Gentry, L.E., M.B. David, F.E. Below, T.V. Royer, and G.F. Mclsaac. 2009. Nitrogen mass balance of a tile-drained agricultural watershed in east-central Illinois. *Journal of Environmental Quality* 38: 1841–1847.

Gliessman, S.R. 2014. *The Ecology of Sustainable Food Systems, Third Edition*. CRC Press: Boca Raton, FL.

IRRI. 2012. Acronyms and Glossary of Rice Related Terminology. www.knowledgebank.irri.org.

Jackson, L., U. Pascual, and T. Hodgkin. 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture, Ecosystems & Environment* 121: 196–210.

Janke, R., J. Mt. Pleasant, S. Peters, and M. Bohlke. 1991. Long-Term Low Input Cropping Systems Research. In *Sustainable Agriculture Research and Education in the Field*. pp. 291–317. National Academies Press: Washington, DC.

Kramer, A.W., T.A. Doane, W.R. Horwath, and C. van Kessel. 2002. Combining fertilizer and organic inputs to synchronize N supply in alternative cropping systems in California. *Agriculture, Ecosystems & Environment* 91(1): 233–243.

Lengnick, L. 2015. *Resilient Agriculture*. New Society Publishers: Gabriola, BC.

Letourneau, D.K. 1997. Plant-Arthropod Interactions in Agroecosystems. In *Ecology in Agriculture*, ed. L.E. Jackson, pp. 239–290. Academic Press: New York, NY.

Liebhardt, W.C., R.W. Andrews, M.N. Culik, R.R. Harwood, R.R. Janke, J.K. Radke, and S.L. Rieger-Schwartz. 1989. Crop production during conversion from conventional to low-input methods. *Agronomy Journal* 81: 150–159.

Little, M.T., and F.J. Hills. 1978. *Agricultural Experimentation Design and Analysis*. John Wiley and Sons: New York, NY.

Marino, P.C. and D.A. Landis. 1996. Effect of landscape structure on parasitoid diversity and parasitism in agroecosystems. *Ecological Applications* 6: 276–284.

Meisinger, J.J., V.A. Bandel, G. Stanford, and J.O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage. I. Four-year results using labeled N fertilizer on an Atlantic coastal plain soil. *Agronomy Journal* 77: 602–611.

National Research Council. 2010. *Toward Sustainable Agricultural Systems in the 21st Century*. The National Academies Press: Washington, DC.

Peterson, C., L.E. Drinkwater, and P. Wagoner. 1999. *Farming Systems Trial*. Rodale Institute: Kutztown, PA.

Puget, P., C. Chenu, and J. Balesdent. 2000. Dynamics of soil organic matter associated with particle-sized fractions of water-stable aggregates. *European Journal of Soil Science* 51(4): 595–605.

Rutledge, C.E., R.J. O'Neil, T.B. Fox, and D. Landis. 2004. Soybean aphid predators and their use in integrated pest management. *Annals of the Entomological Society of America* 97(2): 240–248.

Schipanski, M.E., L.E. Drinkwater, and M. P. Russelle. 2010. Understanding the variability in soybean nitrogen fixation across agroecosystems. *Plant and Soil* 329(1): 379–397.

Shaner, W.W. 1982. Introduction. In *Farming Systems Research and Development: A Guideline for Developing Countries*, ed. W.W. Shaner, P.F. Philipp, and W.R. Schmehl. Westview Press: Boulder, CO.

Shreck, A., C. Getz, and G. Feenstra. 2006. Social sustainability, farm labor, and organic agriculture: Findings from an exploratory analysis. *Agronomy and Human Values* 23: 439–449.

Strock, J.S., D. Bruening, J.D. Apland, and D.J. Mulla. 2005. Farm nutrient management practices in two geographically diverse watersheds in the cottonwood river watershed of Minnesota, USA. *Water Air and Soil Pollution* 165: 211–231.

Vidal, R.A., M.M. Trezzi, R. De Prado, J.P. Ruiz-Santaella, and M. Vila-Aiub. 2007. Glyphosate resistant biotypes of wild poinsettia (*Euphorbia heterophylla* L.). *Journal of Food, Agriculture, and Environment* 5(2): 265–269.

von Bertalanffy, L. 1968. *General System Theory: Foundations, Development, Applications*. G. Braziller: New York, NY.

2

CHAPTER 2

Collaboration, Decision-Making and Organizational Structure for Agricultural Systems Research

Coming together is a beginning. Keeping together is progress. Working together is success.

—Henry Ford

Because agricultural systems research aims to understand agriculture as a complex system, *interdisciplinary research*—research that integrates perspectives and knowledge across disciplines—is generally the most effective approach to use for agricultural systems projects. However, this approach can be challenging because participants must address questions and problems beyond their areas of expertise. Collaborating with scientists from other disciplines can also be difficult because many researchers are accustomed to having a great deal of autonomy and control over their work, and to interacting primarily with others in their own or closely related disciplines. Many scientists may also find it challenging to share decision-making, planning and outreach with nonacademic team members such as farmers, consumer groups or community planners.

And yet, teamwork and participatory decision-making are the cornerstones of successful interdisciplinary systems research. As mentioned in chapter 1, a critical part of systems research is regrouping, which involves changes in how questions are tested. Regrouping also requires using the skills of a diverse team to tackle those questions.

Developing a Collaborative Team

Commonly, collaborative research groups in universities organize as loosely affiliated individuals with a project leader who coordinates the various research components. This "multidisciplinary" mode of working together is the most common approach to collaboration, in part because it requires less time in meetings and allows individuals to work in a business-as-usual way within a larger coordinated project. Using this approach, team members work in parallel and come together periodically to integrate their work. While well suited for some projects, multidisciplinary groups often do not progress beyond a compartmentalized model and typically miss important, complex interactions occurring within the system under study.

In contrast, interdisciplinary research requires the core research group to function as an integrated team. The team members work together at all stages—information gathering, design, implementation and analysis—to obtain a holistic understanding of the system under study.

Effective collaborative teams also use shared and democratically styled leadership, create and foster a group culture conducive to free discourse and participatory decision making, and highlight a group planning process that emphasizes a high degree of interdependence to achieve a common goal.

Role of the Project Leader

Effective, thoughtful leaders are at the heart of successful systems research projects. These project leaders must be thoroughly committed to the project and must employ a variety of skills and techniques to successfully manage multiple participants, ideas, questions and problems.

Project leaders must be aware of their own biases and must genuinely value the diversity of the team they are assembling. They must be open to understanding how scientists from other fields approach their own research and questions and how scientists and nonscientists communicate. They should also be aware of how their own beliefs, values and assumptions influence their leadership style.

Project leaders must also be flexible; agricultural systems research requires the leader's role to continually evolve as the group coalesces into a working team. As the project progresses from planning to implementation, the project leader must guide the team in developing a decision-making framework that encourages innovative problem solving. When the team hits hurdles and bumps, the project leader will need to inspire team members to maintain the shared vision of the project by keeping the focus on the system-level questions and on relating each member's work to these questions.

An effective project leader will also have strong management skills. After initiating the formation of a group with common goals, the project leader must be able to organize the group effectively, set decision-making protocols and guide the team to accomplish those goals. In general, team leaders should strive for a democratic leadership style that allows major decisions to be made through consultation and participation, while maintaining a level of control that corresponds to the leader's accountability for the project. The

Skills Required for Effective Leadership of Collaborative Research Projects

(modified from Clark, 1997)

Communication

- Use clear communication in both individual and group settings
- Listen actively
- Use appropriate interpersonal style(s) to steer team members toward goals
- Delegate decision-making and other responsibilities to appropriate individuals

Interpersonal skills

- Build appropriate relationships and help the team network with peers and associates
- Create a culture of cooperation by facilitating interaction, open communication and participatory decision-making

Professionalism

- Maintain technical competence by staying current on literature and systems and collaborative research methodologies, and by acquiring general knowledge of the other disciplines involved in the project
- Set a good example by modeling consideration of others and by flexibility and adherence to high standards of performance

Recognition

- Praise contributions from participants
- Establish fair and inclusive norms for authorship in scientific publications

Project management

- Set a course, monitor and adapt it (using team decisions), and deal effectively with external forces that influence the team's goals
- Establish norms to foster effective meetings and record keeping, e.g., meeting goals, agendas and documenting meetings through notes and action steps
- Be financially responsible and resourceful, and ensure that funds are distributed fairly

project leader's ability to gauge the level of participation appropriate for a given decision is key to satisfactory group processes. A strong leader will follow through on commitments to the group and will protect the team within the institutional framework by justifying their work to others as an integral part of a larger project.

Effective leaders are trustworthy and provide clear communication of vision (Clark, 1997). These traits establish credibility with prospective team members and increase the likelihood that they will want to participate in a collaborative venture. Being a good listener and staying open-minded, inclusive and adaptive are key.

Project leaders need to keep members engaged and focused and find a balance between providing and sharing leadership. During the initial planning stages, the project leader plays a central role by bridging gaps between disciplines and stakeholders, integrating ideas and helping the group to develop a coherent framework. As team members become familiar with one another's perspectives and working styles, responsibilities can be shared, with different members assuming leadership roles. The leader must consider that agricultural systems research teams require a variety of leadership roles and that careful sharing of leadership can contribute to the project's overall strength. For example, some team members may resist full participation in the project because they did not initiate it and cannot be in complete control of their work. Such members will likely need to assume a leadership role to feel fully invested.

Assembling the Core Team

The composition of the project team is very important to the success of a collaborative project. Usually, the project leader invites participants to join the project. In some cases, an established group may want to use a group process to add new team members.

For successful team selection, begin by choosing colleagues and stakeholders who bring expertise from key disciplines, have compatible personalities and are willing to work in groups. Ideally, people involved in interdisciplinary research should be interested in learning about the theories and methods of other disciplines.

Be cautious about colleagues who lack good interpersonal communication skills or who complain about collaborative work. While collaborative behavior can be learned, avoid working with people who are clearly disinclined to such work. Identify the expectations prospective collaborators have for the project to get a good sense of whether they will be a good fit and to ensure they are engaged in a way that meets their own needs as well as that of the team. Pay attention to the personalities of potential members. For example, does the individual need to be in control of his or her research or is he/she flexible regarding collaborators' expectations for the project? Is he or she willing to let others influence project outcomes and open to using participatory decision-making?

While teams should include a mix of junior and senior faculty, give special consideration when asking untenured faculty to join the project. Be prepared to provide them with adequate support and recognition if they must meet tenure requirements while participating in a collaborative project.

Become familiar with the work of prospective team members by visiting their websites or farms and reading their recent research articles and extension publications—especially when looking for participants outside the leader's discipline and academic circles. Solicit suggestions from colleagues who know researchers in other fields or who have worked with farmers who could be well suited to the project, especially those who have experience with collaboration, are known to work well with others and are willing to assume and share leadership responsibility.

"Selected farmers should have experience collaborating with researchers and have a systems-level understanding of agricultural systems."

In addition to scientists and farmers, seek out farm advisers, extension educators and leaders from other relevant groups, such as farming and environmental organizations. These professionals make good all-around team members; they are intimately familiar with farm operations, bring a different perspective than researchers and farmers, and can be very helpful with data collection and evaluation.

Finally, try to select farmers who are willing to be involved from the project's inception and who can engage with the core team as equals in the decision-making process. Selected farmers should have experience collaborating with researchers. Ideally, they should understand and appreciate the research process, and they should have a systems-level understanding of agriculture and the ability to frame day-to-day farm problems in that context. Farmers on the core team (as well as others who play specific roles in the project) should be compensated financially whenever possible.

BOX 2.1. Farmer-Led Model of Agricultural Research

In 1985, the Practical Farmers of Iowa (PFI), led by a small group of progressive farmers with support from scientists at Iowa State University (ISU), began a farming systems research project. The goal of the project was to develop knowledge and information that would support PFI's vision of sustainable agriculture for their membership and region. Today, the initiative has evolved into a long-term program through which PFI invites ISU scientists to collaborate in setting the research agenda and in obtaining funding. PFI also encourages farmers to conduct research independently of ISU and to make their findings available through farmer-to-farmer training workshops, publications, and PFI's website. The organization has produced detailed guidelines for designing, managing and analyzing research; this research often compares normal farmer practices with experimental management regimes. Information about the research process and outcomes of PFI-led research are available at www.practicalfarmers.org.

Engaging Farmers and Other Nonacademic Stakeholders in Systems Projects

Farmers are key partners in agricultural systems research. Depending on how broadly a team has defined the system boundaries and the project goals, other stakeholders such as extension educators, food distributors, consumer groups, certification specialists, community development planners, natural resource conservationists and policymakers may also be valuable contributors.

Given the wide range of professionals that a systems project may involve, careful thought must be given as to how the team will be managed. There are three basic models for project decision-making and leading: science-led, farmer-led, and interactive (also known as participatory) (Lilja and Ashby, 1999).

The *science-led* model is widely used in conventional research, where the interests and demands of scientific research determine the project plan. Researchers invite farmers to provide information and expertise, but their input is often sought only in the late or final stages of project development.

In the *farmer-led* model, farmers determine the project goals and priorities, and researchers mainly assist with the research aspects (e.g., suggesting the statistical design and data-collection methods). This uncommon approach is gaining influence in regional programs and is a cornerstone of SARE's farmer/rancher grants. SARE producer grants encourage farmers and ranchers to partner with scientists to design and implement research addressing innovations they wish to test on their farms. The Practical Farmers of Iowa have also implemented a successful farmer-led research process (Box 2.1).

The *interactive* model of leadership links farmer researchers with scientists and requires them to work closely together throughout the lifespan of the research. Researchers and farmers are equal participants in developing goals and priorities for the group, and joint decision-making occurs at the earliest stages. Known in some circles as participatory research, this type of decision-making is becoming more common and is the most effective method for researcher-led projects because close involvement from experienced, knowledgeable farmers helps ensure that the project will reflect true agricultural systems.

Practical distinctions among the three models are a matter of degree. Sometimes, funders specify the roles of various stakeholders. Ideally, agricultural systems research includes participation by stakeholders outside the university. To facilitate effective interactions between scientists and farmers, prospective leaders need to be prepared for a range of challenges and able to identify viable solutions (see SAFS case study, p. 35).

Farmers and others outside academia face unique barriers when participating in agricultural systems research, and project leaders should be prepared to address these challenges. While participation in formal research is required of professional scientists, it is not usually necessary in other stakeholders' professions. The challenge is to tie the research to outcomes that nonacademic stakeholders will find interesting and useful and that will encourage their participation. Compensating stakeholders for the time they commit to project meetings and for travel can also encourage participation.

Challenges to and Strategies for Keeping Farmers Engaged

Forming sustainable partnerships between the research community and farmers is an ongoing process that requires negotiation, patience and persistence. Begin with gradual establishment of trust, communication and shared philosophy during proposal development to allow relationships to develop with friendship, openness and continuity. This approach will also support farmers' engagement with the project and can help extend mutually beneficial farmer–researcher relationships beyond the final publications and grants.

Research priorities will often differ between the two groups; be sure to discuss how those different goals and constraints affect the collaboration. Scientists are generally most interested in generating a new understanding of how systems work, while farmers want to solve current problems and improve their farming systems. These differences will determine how research goals are prioritized. Make sure to communicate how the research is relevant to farming and make a real effort to include farmers' priorities in the research plan. Farmers and academic collaborators should be treated equally.

Both farmers and scientists lead busy lives and may be reluctant to attend meetings, especially if they do not see clear outcomes. Therefore, be conscientious about making efficient use of meeting time. Farmers should know why the researchers seek their participation in a meeting and what is expected of them. When time is short, representative scientists and farmers can be designated to meet on behalf of the research team. This works well for fine-tuning group decisions or for day-to-day management decisions, but it is not a substitute for group process. Conference calls or webinars can also be used.

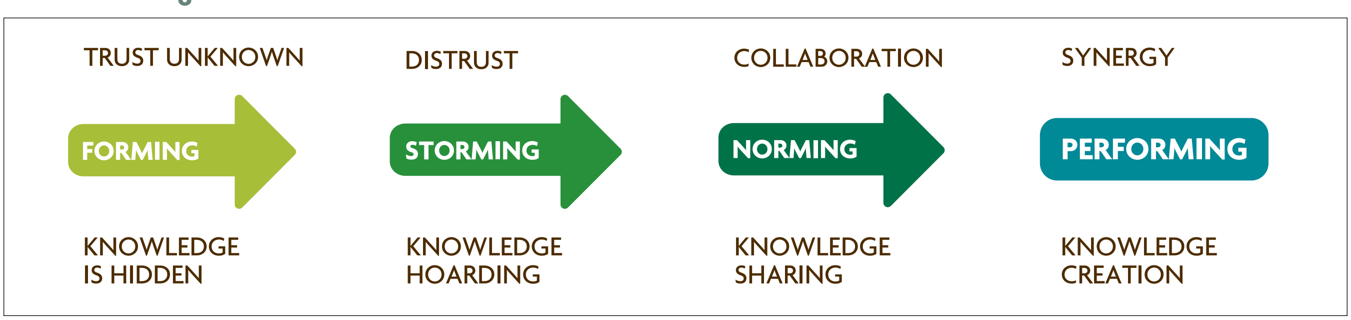
Sometimes, projects can stall over mechanics. For example, considerations and constraints on plot design differ between on-farm trials and research stations because of equipment and resources such as labor. These differences need to be addressed when planning experiments in which farmers contribute to the design or provide research sites on their farms.

Keep in mind that unlike researchers, farmers do not earn their living from research and meetings. Thus, farmers should be compensated for their time and expertise, just as other professionals would expect to receive compensation. There are a number of strategies for compensating growers, including:

- Pay as you go: Farmers can be treated as consultants and paid on an hourly basis for well-defined activities. For example, they could be paid $25 to $35 per hour for participation in meetings.
- Annual stipend: Farmers can be offered a fixed annual stipend that reflects their level of involvement. Creating a detailed plan of the farmer's participation helps determine that level; in general, annual stipends range from $200 to $2,500.
- Outcome-based compensation: Rather than being compensated for time, farmers can be paid for specific contributions. For example, a project that aimed to educate farmers through farmer-to-farmer transfers paid expert farmers for maintaining a farm website with specific attributes.

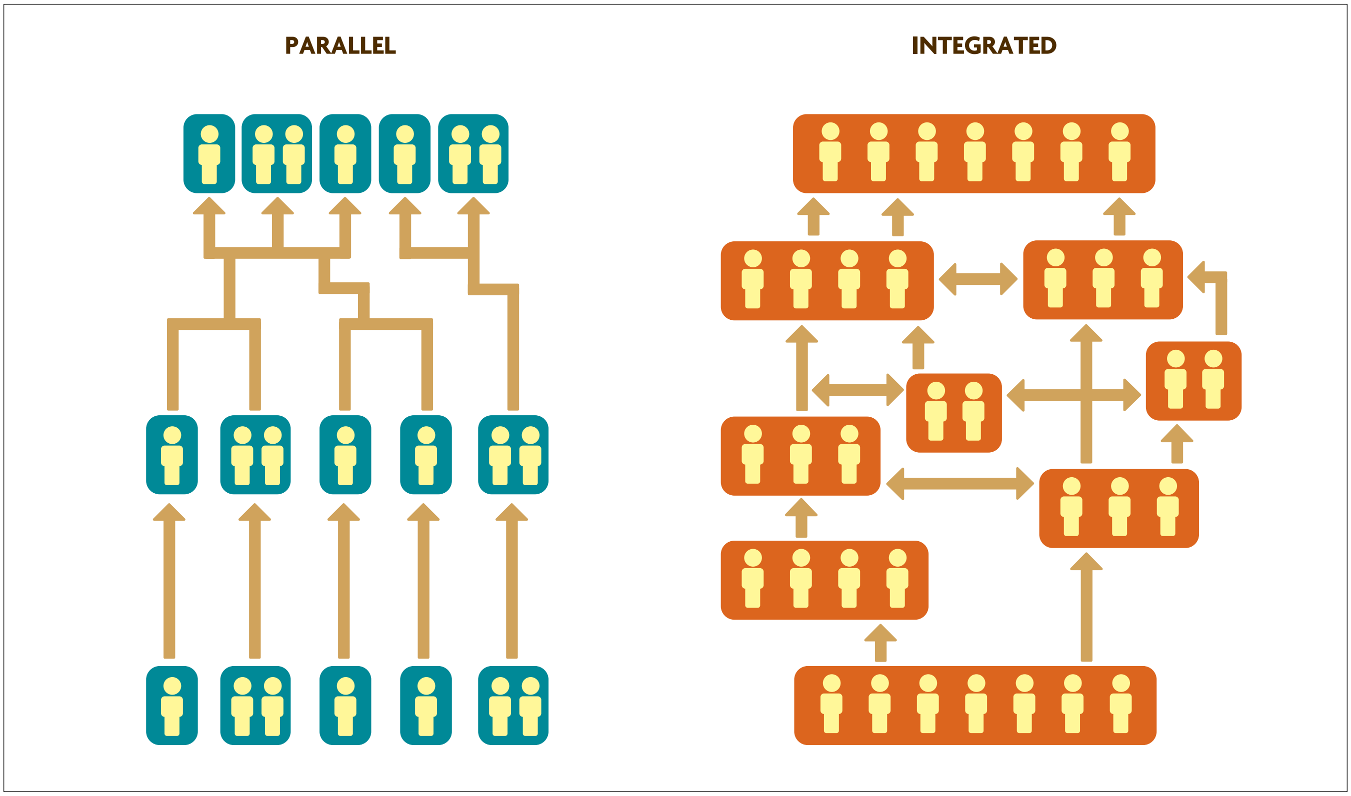
There are also multiple strategies to engage farmers, such as creating opportunities for farmers and researchers to meet regularly at coordinated site visits and annual winter workshops. Increasingly, networks of farmers are sponsoring on-farm research and public field days, workshops and demonstrations. Tapping into these events and into farmer-to-farmer networks that are familiar with or interested in research will go a long way in relationship building and can provide an entry point to engage farmers in diagnosing problems that lead to good research questions. Developing a process to bring new farmers into the program, e.g., by inviting them to annual spring forums to meet researchers and other farmers, will help facilitate interactions between newcomers and veterans that will help generate credibility with the farming community.

FIGURE 2.1. Stages in the Formation of a Collaborative Team



This four-step pattern was proposed by Tuckman (1965) and modified from Clark (1997).

FIGURE 2.2. Parallel and Integrated Project Design



In a parallel project design, subprojects are brought together toward the end for integration, and contributions of the individual subprojects are identifiable in the end product. In an integrated project design, used by interdisciplinary teams, participants work together throughout the project from design and conception to completion and publication. Achievements are a product of all participants, and the efforts of individual disciplines or subgroups are difficult to identify. From Tress et al. (2005).

Instilling a Culture of Collaboration

Social scientists have long recognized that groups go through distinct stages in the process of becoming a team (Figure 2.1). Tuckman (1965) developed a widely used model of team evolution, proposing that as individuals form a team with a common purpose, the group tends to follow a pattern consisting of four stages:

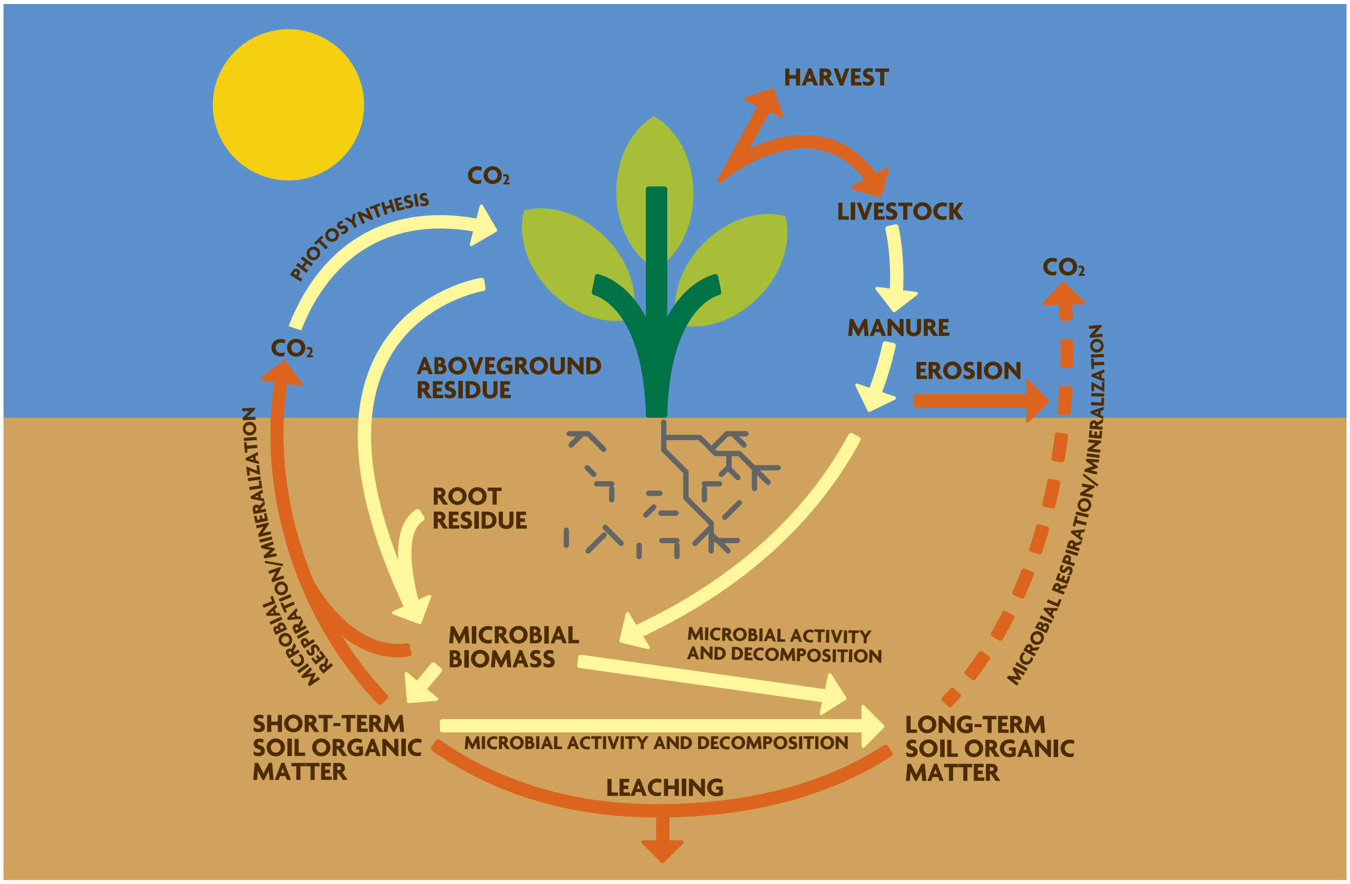
- Forming: the group comes together for a purpose.
- Storming: the group struggles to establish a productive working relationship and to agree on priorities.
- Norming: the group establishes standards for accomplishing its goals.
- Performing: the group begins to function well as a whole.

Recognize that it is normal to face challenges during the development of a collaborative team; this will help the group have realistic expectations. The storming phase can be stressful if the group does not realize that conflict and discomfort are common during collaboration. Frequently, this stressful period occurs as team members struggle to make the paradigm shift from a reductive, component-oriented approach to an interdisciplinary, systems-level approach. The group should try to view the growing pains associated with storming as a normal part of developing relationships that provide the foundation for teamwork.

The transition from *storming* to *norming* is often initiated by successful adoption of common goals and objectives, which form cooperative strategies that become part of the team culture. The following list provides guidelines on how to develop a collaborative culture for agricultural systems research:

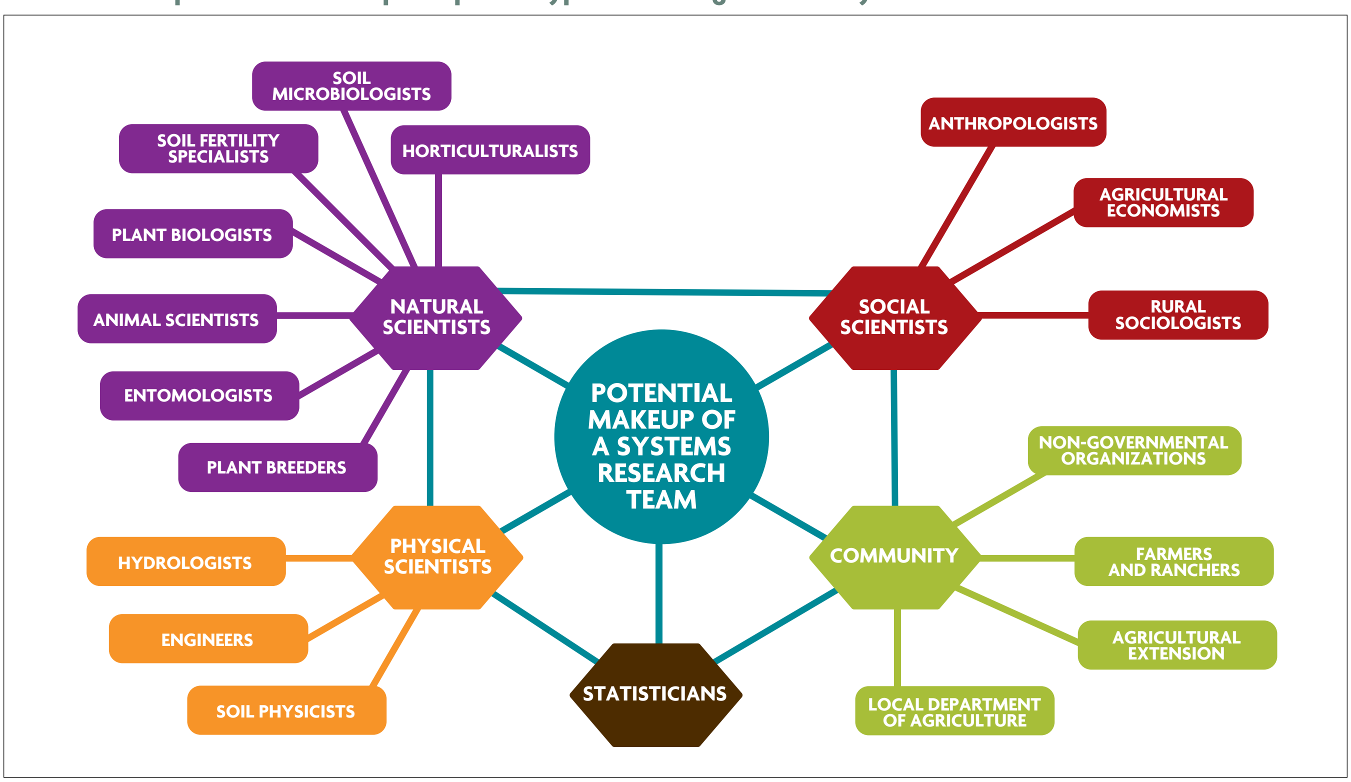
- Establish a project timeframe that is long enough for iterative decision-making and regular patterns of interaction.
- Initiate frank discussions among members of the research group about collaborative work and decision-making. The group should discuss the differences between centralized and participatory decision-making, parallel

FIGURE 2.3A. Systems Concept Map of the Carbon Cycle



Adapted from Cavigelli et al. (1998).

FIGURE 2.3B. Spider-Web Concept Map of a Hypothetical Agricultural Systems Research Team



and integrated organizational structures, and the various types of interdisciplinary approaches. A democratic form of decision-making is recommended, but regardless of what form is chosen, leaders should ensure that everyone understands it.

- Embrace a facilitative leadership style; encourage team members to participate in guiding meetings and to take responsibility for achieving the project goals.
- Start the process of team integration at the beginning of the project, and plan a combination of regular meetings and informal discussions.
- Develop a common language, limiting jargon and specialized terms that may not be understood or defined similarly across all fields. Acknowledge that this will take time, and allocate extra time for cross-disciplinary exchanges.
- Develop an open, honest culture of communication. Each person should be free to express how they see their role in the larger project as it unfolds. Check in with each individual to see how they feel about the group dynamics, and be prepared to address feedback in a respectful and constructive way.
- When possible, combine the process of project planning, goal development and proposal writing with socializing (e.g., a group meal) to support the evolution from a group with common interests to a working team.
- Decide what information will be exchanged among disciplines to promote communication and understanding of other disciplinary perspectives; set a timeline for disseminating this information.
- Educate new members about the team's integrative approach to research and its collaborative work style. Leaders should not assume that new members will independently catch on to the complex project environment.
- Discuss how to deal with the loss of team members who depart before the project's end, and share responsibility for filling the vacancy and integrating new members into the team.

Using Concept Mapping to Build Collaborative Teams

Concept mapping is a useful tool for building shared cognition, an essential building block of interdisciplinary research that can help team members understand one another's disciplinary perspectives on a problem. Concept maps visually represent ideas around which common goals can be articulated; they convey meaning efficiently and aid in understanding complex information at a glance.

Participatory concept mapping begins with identifying a key problem or question that is fundamental to the research. A facilitated discussion helps ensure a common understanding of the words used to depict the problem. From there, the team can work in a *parallel* or *integrated* fashion to elaborate the causes and consequences of the problem and the relationships among these causes and consequences.

Using the *parallel* model, the facilitator asks each participant to create a concept map and then share it with the group. By helping the group compare and contrast the images, the facilitator helps the team to arrive at one common map.

In the *integrated* method, the facilitator has the group brainstorm plausible causes and effects and uses these inputs to help the group construct one common concept map that depicts relationships among the factors. This product is then used to develop the systems project concept map, which defines the system or problem to be studied.

Concept maps can be represented in various formats, including hierarchies, landscapes, systems or spider webs. Figures 2.3A and 2.3B depict systems and spider-web concept maps. For further discussion of how to use concept mapping to plan experiments, see chapter 3.

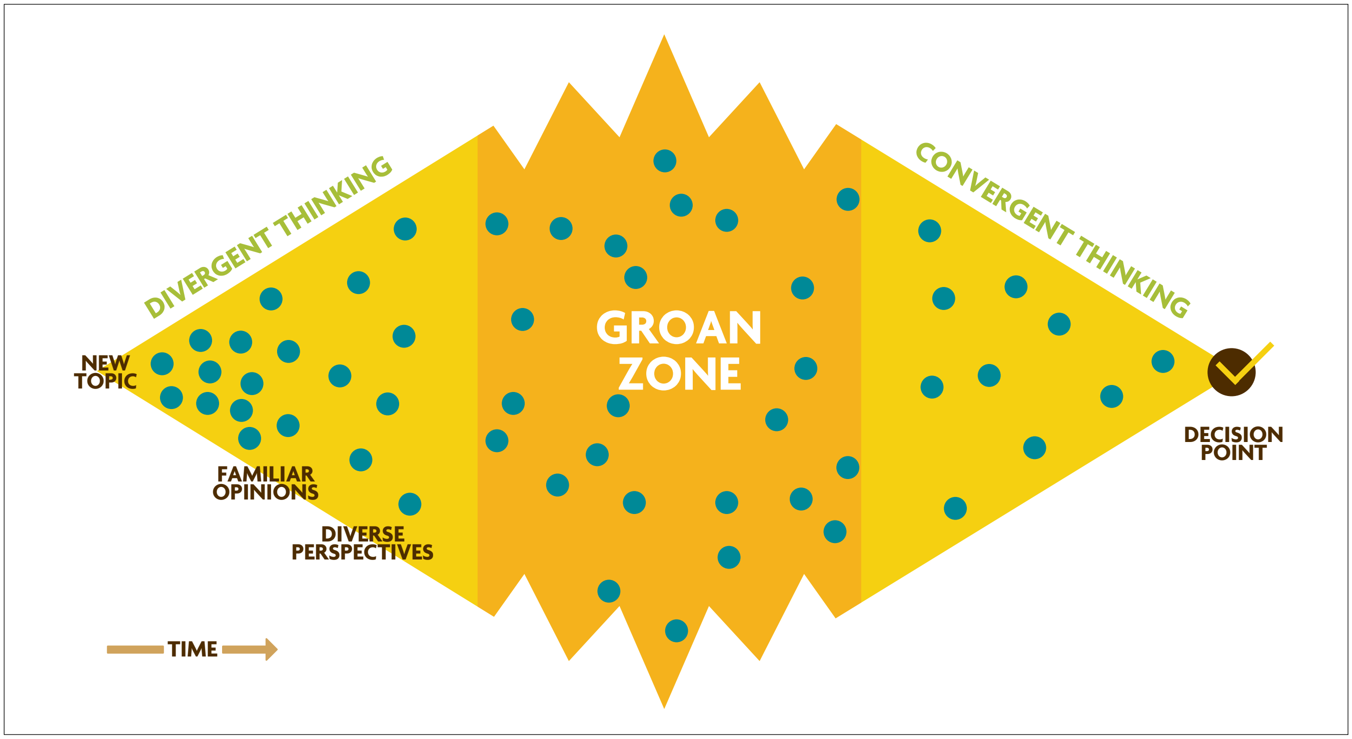
Facilitating Participatory Decision-Making

Participatory decision-making in an interdisciplinary research team is challenging. While the team may easily identify a common goal, there are likely to be as many perceived pathways for reaching that goal as there are team members. However, democratic decision-making is essential for effective collaboration. The decision-making process is most visible in meeting settings, so the way in which meetings are conducted, especially around decision-making, affects the culture of collaboration.

Elements of Participatory Decision-Making

The "Diamond of Participatory Decision-Making," by Kaner and colleagues (2014), provides one example of what participatory decision-making looks like as it aims to integrate diverse perspectives (Figure 2.4). Blue dots in the figure represent ideas shared among the group during the meeting. As familiar options give way to diverse perspectives, an unpleasant period of interaction occurs that can involve repetition, interruption, defensiveness and short tempers. The authors call this inevitable stage the "groan zone," during which participants struggle to understand a wide range of foreign or opposing ideas. Significant creative

FIGURE 2.4. **Diamond of Participatory Decision-Making and the Groan Zone**



This schematic illustrates the awkward but normal dynamics of decision-making among team members with diverse perspectives. Understanding how divergent thinking can coalesce into good decision-making can help facilitators tap the enormous potential of the group process. Blue dots represent ideas shared among the group during the meeting. From Kaner et al. (2014).

breakthroughs evolve from this uncomfortable period if the process is facilitated in a caring and competent way.

The dynamics of the groan zone will be most apparent early in the project, when team members are becoming acquainted and developing relationships (the storming phase). At this formative stage, bring this dynamic to the group's attention and be deliberate in facilitating the group through it. Later, when the group has transitioned to interacting as a more cohesive team, less time will be spent in "groan-zone" mode.

Kaner and colleagues (2014) identify six decision rules commonly used in participatory decision-making: (a) unanimous agreement (consensus), (b) majority vote, (c) person in charge decides without discussion, (d) flip a coin, (e) delegation, and (f) person in charge decides after discussion. A conventional project leader is likely to default to the "person in charge decides after discussion" rule. A team leader using the integrative or participatory method should challenge this assumption and help the team choose the best option.

Becoming a Good Facilitator

Skillful facilitation is essential for effective interdisciplinary decision-making; it fosters interaction, joint learning and participatory decision-making, it aids in building collaboration (Heron, 1999; Straus, 2002), and it helps a group do its best thinking (Kaner et al., 2014). A good facilitator eases the team through the groan zone by pointing out that this phase is normal and by using a variety of tools to help the team reach convergence of ideas and inclusive solutions.

A good facilitator will:

- Delegate responsibilities to all team members
- Prevent experts in certain fields from controlling meetings
- Encourage all team members to participate
- Ensure that everyone in a meeting works on the same problem using the same strategy
- Promote mutual understanding
- Foster inclusive solutions.

Useful Facilitation Techniques

Brainstorming, equivalent to "rough draft thinking," involves a group drawing a list of ideas about what to do about an identified problem or need. A successful brainstorming session will: (a) encourage people to take turns; (b) treat all ideas with the nonjudgmental responses (verbal and nonverbal), regardless of how unreasonable or unrealistic an idea may sound; (c) create a lively atmosphere for the discussion; and (d) help the group keep time. It is important not to: (a) interrupt, (b) judge, (c) favor the "best" thinkers, (d) give up the first time the group seems stuck, (e) rush or pressure the group, or (f) fail to set a time limit.

Breaking into small groups provides an alternative to open discussion. Small groups are effective for: (a) breaking the ice so people feel less exposed and therefore less reserved, (b) energizing people through activity, (c) deepening everyone's understanding of a topic because there is more time to explore each person's ideas, (d) exploring different aspects of a problem simultaneously, (e) building relationships, and (f) generating a greater commitment to the outcome.

Stacking involves organizing the flow of an open discussion to allow people to take turns when several want to speak at once. Instead of competing for a chance to speak, people are free to listen. Stacking also enables a group to break habitual patterns of deference and favoritism. It is sometimes the simplest way to get a rigidly hierarchical group to make room for participation from low-status members. To facilitate stacking, poll the members about their interest in speaking about a topic or question raised. After a show of hands, make a list of names and call on each in turn for their contribution. When everyone on the list has spoken, depending on the time available and the importance of the issue, poll the group again to see who would like to expand on or offer a rebuttal to what has been said. Continue until it feels comfortable to bring the process to a close.

Structured go-around is a useful technique for framing a complex discussion, gathering diverse perspectives, returning from a break after a heated disagreement and coming to closure. The go-around occurs in a circle format so everyone's face is visible. The main ground rule is that one person speaks at a time after the facilitator gives a brief overview of the topic.

The importance of developing basic facilitation skills cannot be overemphasized. That said, it may be unrealistic to expect agricultural scientists to also be expert facilitators; bringing in professional facilitators to help the project get started may be a good way to bridge this gap.

As the benefits of facilitative leadership become increasingly recognized, agricultural colleges and universities are beginning to offer training workshops for scientists, educators, farmers and other professionals working on agricultural systems research. Project leaders should consider attending such a workshop. If the project can afford it, a reputable facilitator can organize a training tailored to the project's needs that can help the team gain the insight and skills needed to share leadership responsibilities effectively.

Planning and Conducting Effective Meetings

While meetings are important, nothing can ruin a collaboration faster than long, drawn-out get-togethers in which participants feel little is accomplished. Learning to conduct effective meetings is a key skill for collaborative groups in planning and carrying out agricultural systems research.

When the project team is forming, the group will spend more time in meetings to build the foundation for collaboration and to allow for discussion and exchange of ideas. After members have become familiar with one another and with their respective disciplines, meetings should focus more on planning and decision-making. If there are too many meetings, involvement will be viewed as a burden and participation will lag.

A good meeting begins with a clear purpose and a carefully planned agenda; it ends with a brief review of accomplishments, a list of action steps and an evaluation of the meeting. The atmosphere should encourage participation and progress toward shared goals. The group should make decisions using a transparent process that everyone understands and should deal with difficult dynamics constructively.

Planning the Meeting

Consider the purpose of the meeting. Review the big-picture goals to plan how work will be spread out over a series of meetings and to determine when major activities will take place. Avoid trying to get too much done in one meeting; team members will be exchanging ideas and information between meetings. Save important decisions, or welcoming new members to the group, for a meeting. A few other tips:

- Determine if everyone needs to attend. Some project decisions can be made by the core scientific team alone, while others will require that farmers and other team members be present.
- Once the team has formed and the project becomes regularized, strive to keep meetings short and efficient. Participants will be more willing to attend subsequent meetings if they feel their time is being used well.
- Consider strategies for dealing with the distance some participants may need to travel, such as varying the location or using conference calls, Skype or webinars. If team members are widely distributed, consider building an extended meeting around an activity of common interest, such as a conference, to help justify the travel time and cost.
- Prioritize agenda items by their importance to most participants. Assign realistic amounts of time to each agenda item.

To help make meetings efficient and inclusive, always take the following basic measures:

- Plan for the meeting, and prepare yourself and other participants for it in advance.
- Solicit agenda items from all team members.
- Determine what information is necessary for decisions that need to be made, and send materials out beforehand.

During the Meeting

Assign the roles of (1) facilitator, (2) recorder, and (3) timekeeper. Different individuals can assume each role or one person can assume all three.

Decide as a group which rules to use for making decisions. To review the basic options, refer again to p. 31–32 on rules for reaching agreement. Different rules can be applied to different decisions depending on their significance to the future of the project. The team may want to use consensus when buy-in from each member of the core team is important to their continued engagement. Majority rule may be sufficient when deciding when to hold an event that not everyone needs to attend. The "person in charge decides" rule can be applied for certain administrative decisions.

Establish a code of conduct for participants. Although academic culture may accept interrupting and authoritarian posturing, collaborative work is more effective when communication is polite and egalitarian. Consider a sample code of conduct that encourages meeting participants to:

- Listen carefully to others
- Respect different opinions
- Be acknowledged by the facilitator before speaking
- Refrain from interrupting.

As the group moves through the agenda, abide by the established timetable. If members cannot reach closure on certain items in the time allowed, propose a viable alternative process for doing so.

Bring closure to the meeting by:

- Confirming major decisions
- Reviewing action steps
- Evaluating the meeting
- Planning for the next meeting.

SARE CASE STUDY SAFS: Systems Research Using Participatory Decision-Making

Photo courtesy of Jill West

The Sustainable Agriculture Farming Systems (SAFS) study, begun in 1988, was a pioneering systems project at the University of California (UC), Davis that looked at best farming practices in two- and four-year rotations of tomatoes, safflower, corn, wheat and dry beans. The objective was to generate information on sustainable growing techniques that would be of practical use to producers in the Sacramento Valley. A key to the project's success was the close collaboration and involvement of farmers.

"From beginning to end, farmers were intimately involved in the planning, the execution and the interpretation of results," says UC Davis agronomist Steve Temple, who coordinated the SARE-funded project.

Including farmers on this team provided multiple, crucial "reality checks" for research plans, as one example from the early years shows.

The researchers had designed a study that involved seeding tomatoes in organic, low-input and conventional test plots all on a single day. The intention of same-day planting was to create a level playing field for the plants that would simplify data analyses later.

However, producers recruited to work with the research team offered a dose of reality, noting that conventional and organic or low-input farmers would not plant tomatoes on the same day. Conventional farmers would plant sooner to take advantage of early market incentives, while organic and low-input farmers would wait to give their cover crops more time to grow and would use transplants rather than seeds to make up for the late start.

The researchers took their producer colleagues' advice. They direct-seeded the conventional systems in late March and put transplants into the organic and low-input systems two weeks later. In the end, they demonstrated that transplanting in organic and low-input systems effectively increased yields.

Incorporating farmer input "made the research more difficult, but it made it more realistic," says Bruce Rominger, one of the producers involved in the decision.

As another example of the important contribution made by growers, Temple points to one year's corn yields. The low-input system had far outperformed the conventional system, and researchers initially attributed the performance to better nitrogen nutrition in the low-input system.

But when growers examined the results and walked the test plots, they noticed a major difference in how the systems had been planted. Corn was planted in two rows per 60-inch bed in the conventional system and in single-row, 30-inch beds in the other systems. This meant that the conventionally grown corn had less access to ground moisture, which is why it did not perform as well. "To sort it all out, we really counted on farmers to visit the plots and look over the data," Temple says.

In the beginning, project organizers put a lot of time into working with cooperative extension to identify farmers in the area who would be a good fit for the project. Temple says the goal was to represent a variety of backgrounds.

Growers in the SAFS project were not compensated. However, Rominger says he found the experience invaluable because it put him in touch with cutting-edge research that he was able to apply to his own operation—about 3,000 acres of both organic and conventional crops. In any research project involving farmers, he says, it is important to recruit growers who have already expressed an interest in the topic or in research in general, rather than to try to bring in people who do not appear interested. That is because a healthy relationship between farmers and researchers relies on mutual give-and-take.

Photo courtesy of Jill West

Growers need to be patient with researchers, who do not have the freedom to move as fast as growers do on the farm. "Farmers are used to deciding something and then doing it the next day," Rominger says. "At universities, it just doesn't happen that way."

Also, Rominger says it became frustrating to sit in meetings where funding was discussed at great length—a topic that is essential to any research project, but one that farmers cannot help with. He suggests that project coordinators keep farmers in the loop on funding issues but that they remain mindful not to spend much time discussing funding, or similar issues of little interest to farmers, on farmers' time.

Systems researchers who involve farmers "need to truly want to use that input and not just do it because the foundation that funded them wants farmers on board. That attitude is not going to take you very far," Rominger says.

References

Cavigelli, M.A., S.R. Deming, L.K. Probyn, and R.R. Hardwood, eds. 1998. *Michigan Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality*. Michigan State University Extension Bulletin E-2646: East Lansing, MI.

Clark, D. 1997. *The Art and Science of Leadership*. www.sos.net/~donclark/leader/leader.html.

Heron, J. 1999. *The Complete Facilitator's Handbook*. Kogan Page US: Sterling, VA.

Kaner, S., L. Lind, C. Toldi, S. Fisk, and D. Berger. 2014. *Facilitator's Guide to Participatory Decision-Making, Third Edition*. Jossey-Bass: San Francisco, CA.

Lilja, N., and J.A. Ashby. 1999. *Types of Participatory Research Based on Locus of Decision Making. Participatory Research and Gender Analysis Working Document 6*. Consultative Group on International Agricultural Research: Cali, Colombia.

Straus, D. 2002. *How to Make Collaboration Work: Powerful Ways to Build Consensus, Solve Problems, and Make Decisions*. Berret-Koehler Publishers: San Francisco, CA.

Tress, B., G. Tress, and G. Fry 2005. Integrative studies on rural landscapes: Policy expectations and research practice. *Landscape and Urban Planning* 70: 177–191.

Tuckman, B.W. 1965. Development sequences in small groups. *Psychology Bulletin* 63: 384–399.

3

CHAPTER 3

Planning Interdisciplinary Agricultural Systems Research

An approximate answer to the right problem is worth a good deal more than an exact answer to an approximate problem.
—John Tukey

A well-constructed research plan always follows four basic steps (Friedland and Folt, 2000):

- Development of one or more hypotheses to address important questions
- Application of the most appropriate methods to test the hypotheses
- Interpretation of results and synthesis of the findings
- Timely dissemination of results.

Agricultural systems research is no different; it proceeds through all of these steps, but the specific nature of this type of research, and the fact that it is often carried out by interdisciplinary groups with expertise in a wide range of disciplines, presents unique challenges. In particular, preliminary steps, such as defining the problem and setting goals, as well as the steps mentioned above—especially developing an appropriate experimental design—are more difficult in interdisciplinary groups where members often lack a shared paradigm or language. Furthermore, scientists and practitioners often have less experience with systems-based studies than with the more common reductionist approaches that require less intensive collaboration.

Defining the Project Scope

Collaborative research is most successful when it progresses sequentially through the steps of project development. The process begins with sharing knowledge and information, moves to defining the problem and setting goals, and then to developing the questions and hypotheses that form the basis for the experimental plan.

Figure 3.1 shows how a team can move from general to specific planning and depicts the importance of revisiting issues as a project develops. For example, budgets and other resources need to be planned in the early stages, but as the team sets goals and objectives and moves through the final planning stages, the budget should be adjusted as allocations for each objective are identified and tweaked. (Reallocation of financial resources for projects funded at different levels than proposed is covered in chapter 5.)

Information Gathering and Literature Review

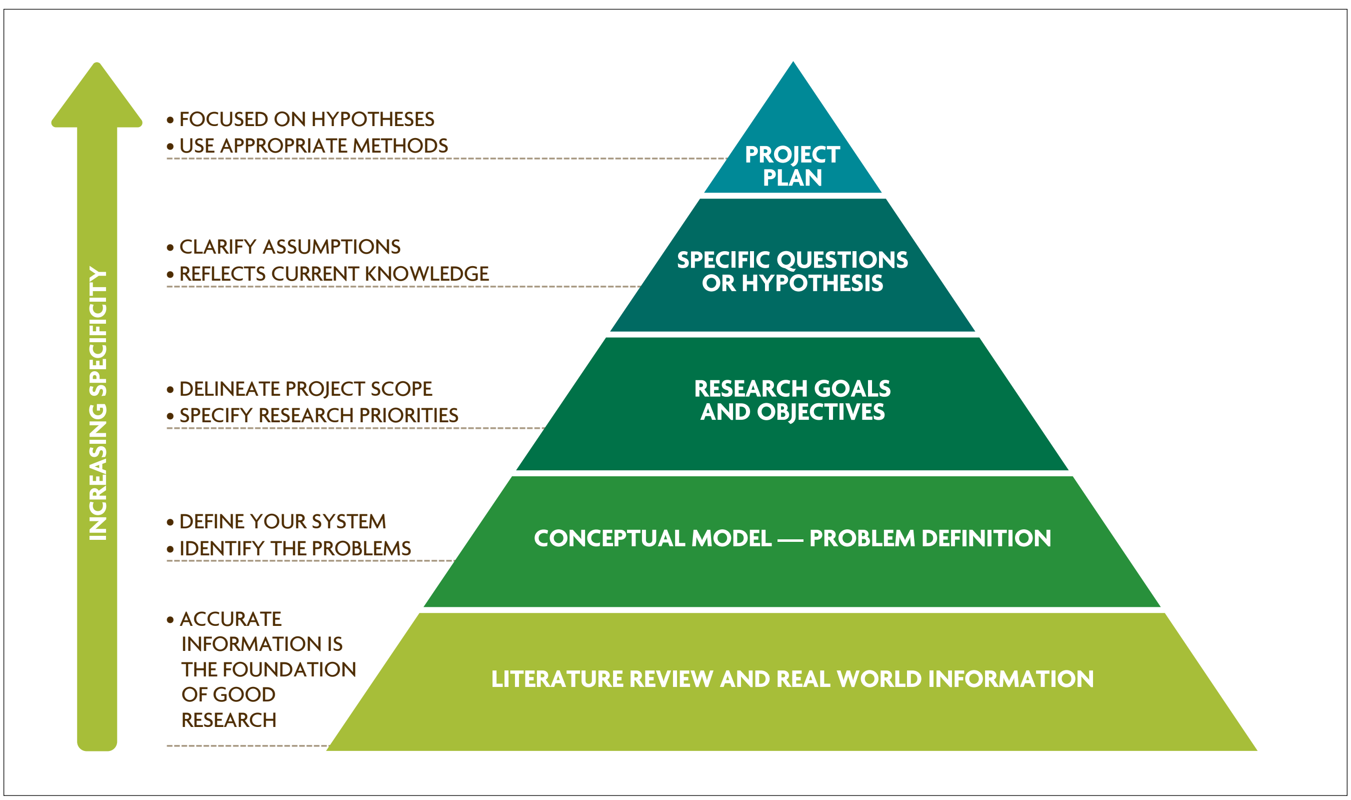
Scientists cannot develop research questions in a vacuum. As with all scientific inquiry, defining problems and formulating research questions and hypotheses must occur in tandem with thorough knowledge of the pertinent literature. In agricultural systems research, this knowledge is usually supplemented by information not generally available from scientific journals, such as agronomic, ecological and economic knowledge of local and regional farming systems, and farmers' observations of and familiarity with local farming systems. This "unpublished" information is particularly important for agricultural systems research that aims to improve local production systems.

Although scientists and practitioners bring knowledge of the literature and varying degrees of familiarity with local and regional production systems to a project, knowledge gaps often become evident as problems are framed and the experiment is developed. These gaps can be addressed by having the team brainstorm about what information is needed to move the project to the next stage and then by dividing up the task of collecting this information. The broader the range of disciplines represented on the team, the more important it is to foster cross-disciplinary exchange of basic information, which ultimately forms the foundation of the project.

Identifying the Problem

In traditional research settings, most people classify problems according to their area of expertise and then create a

FIGURE 3.1. The Process of Project Development



Based on steps outlined by Friedland and Folt (2000).

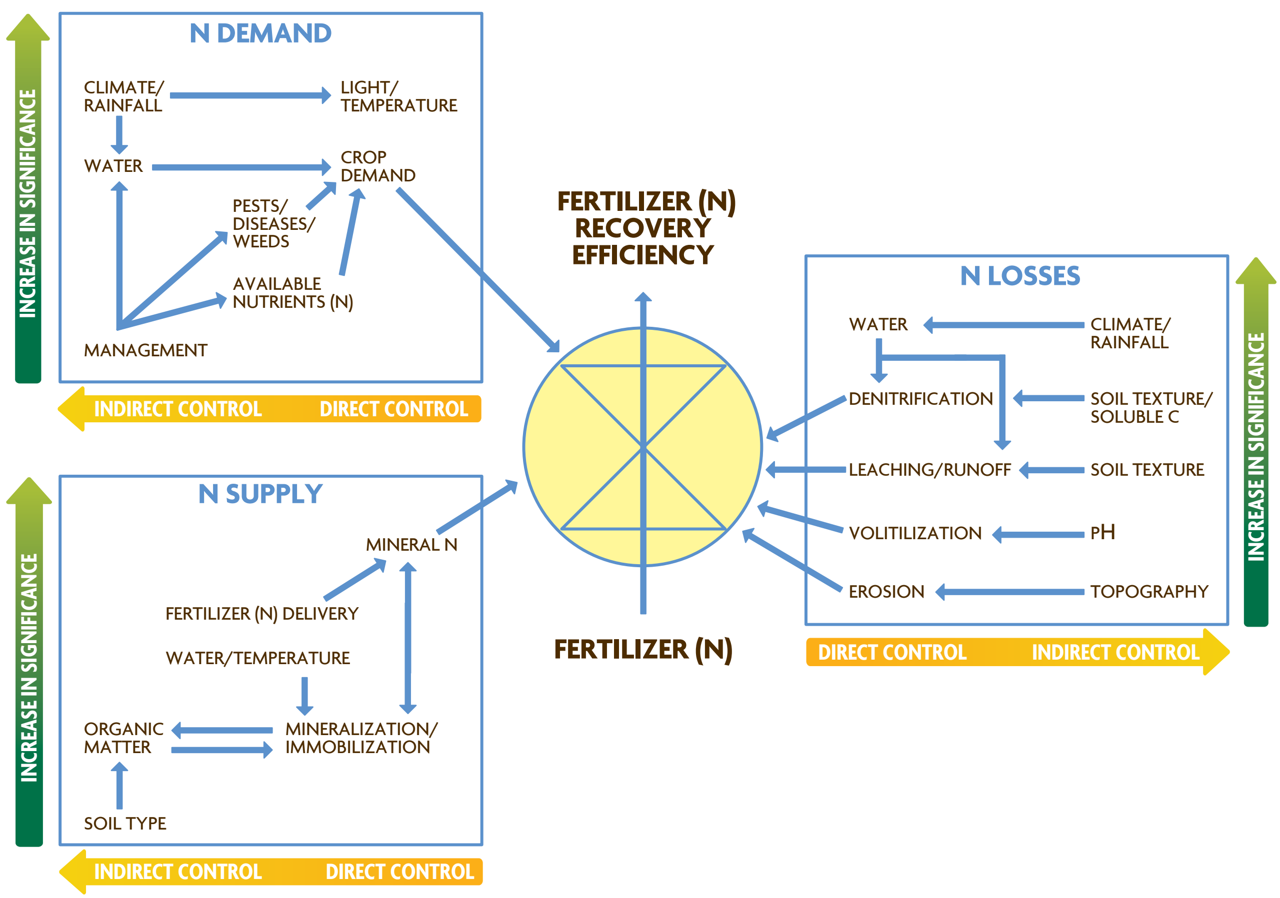
"mental map" of their research program. These maps typically include broad goals, assumptions about the question or problem under study, a series of questions to be addressed and a plan for how the results will be used to move to the next stage of inquiry.

An interdisciplinary team working on agricultural systems research must move beyond fragmented, discipline-oriented definitions of problems. The problem must be framed to integrate diverse perspectives and to form a logical basis for reaching goals and answering research questions.

Consider, for instance, the roles that different experts can play in developing approaches to remediate nitrogen runoff. In a conventional research setting, each scientist and practitioner would view the problem through his or her disciplinary lens and would focus on tackling that part of the problem. In contrast, an interdisciplinary approach would require integration of distinct perspectives to provide linkages among system components that would be evident to each team member. Using this approach, the team would develop a broad model that portrays how system components interact to contribute to the problem. This model could include field-scale biophysical processes, landscape characteristics that influence fertilizer loss, and socioeconomic processes that influence farmers' management decisions. Figure 3.2 depicts three conceptual models of impacts and factors that contribute to nitrogen use and pollution from a systems perspective, each generated by a team with different perspectives and priorities.

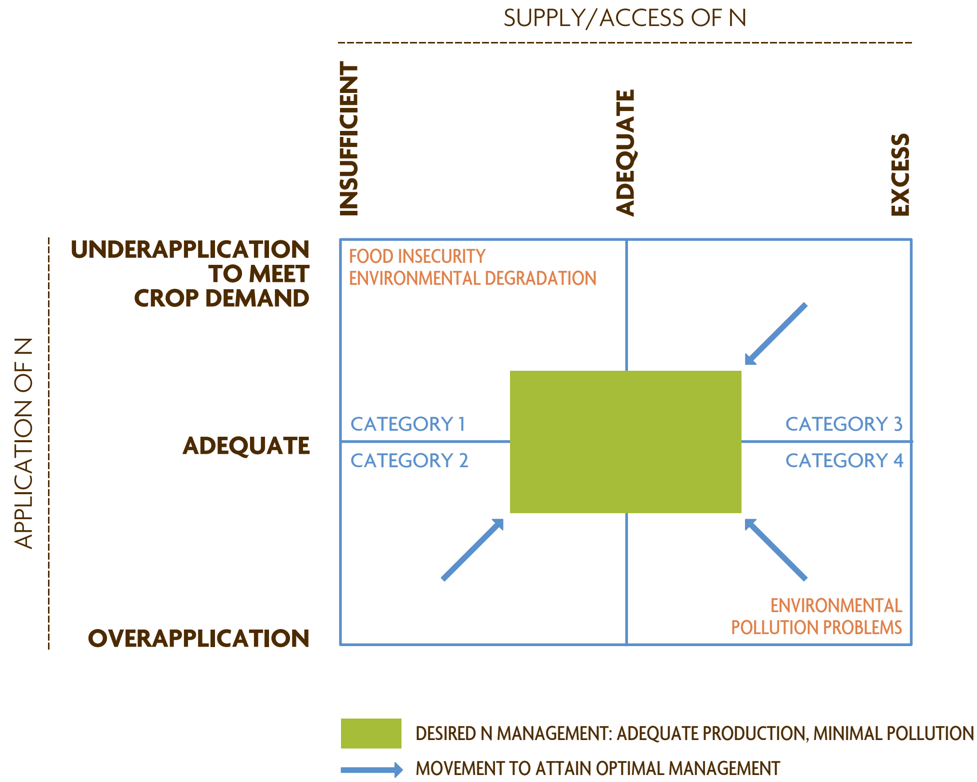
FIGURE 3.2. Three Conceptual Models of the Drivers and Consequences of Fertilizer Nitrogen Management

Figure 3.2A. Crop, Environmental and Management Factors Affecting Nitrogen Use Efficiency



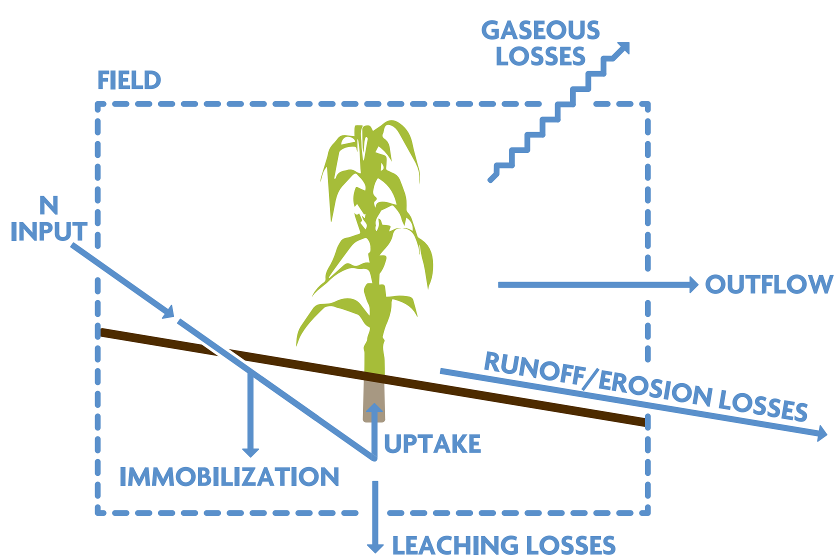
Conceptual model depicting the three main controlling processes (nitrogen demand, supply and losses) and the major mechanisms and factors regulating fertilizer N use efficiency. The symbol in the center represents the "control center," which influences the flow of fertilizer N into the crop. From Balasubramanian et al. (2004).

Figure 3.2B. Societal Responses for Addressing Nitrogen Fertilizer Needs: Balancing Food Production and Environmental Concerns



Conceptual model showing the range of N access/supply, N application patterns that emerge at the national level, and effects on food security and the environment. From Palm et al. (2004).

Figure 3.2C. Pathways of Nitrogen Loss and Their Impacts on Human Health and the Environment



Conceptual model showing interactions between N input and N loss processes. From Peoples et al. (2004).

To be useful as a project planning tool, a concept map should:

- Describe a system that encompasses the research questions
- Have clear boundaries
- Define the system components and their interactions
- Provide a logical framework for the research questions
- Be developed and agreed upon by all collaborators such that each person can find his or her subsystem or area of expertise in the model
- Be understandable to reviewers, stakeholders and potential funders.

Concept maps, as discussed in chapter 2, make a useful starting point for interdisciplinary collaboration because they require a team to graphically represent the research problem within a larger systems context (Heemskerk et al., 2003). This ensures that everyone in the group begins with the same picture of the complex system and problem. Thus, in addition to the team-building function, a conceptual model is indispensable in formulating a research plan.

Establishing Goals and Objectives

Once the research team agrees upon a conceptual model of the system or problem that will be the project focus, it can move to the next stage of developing project goals and research questions, where cross-disciplinary syntheses often emerge.

At this early stage, it is easier to include everyone's ideas about goals and questions than to condense or set priorities, so teams should be inclusive. However, this can lead to unwieldy projects with too many goals that are too diffuse to be managed effectively, so the group will eventually need to limit the project goals by setting priorities. The team leader's ability to facilitate project development will be crucial at this juncture. The leader must ensure that the group considers how well the goals and priorities balance the interests of different disciplines and stakeholders and whether they are a good fit for the project as a whole. Each participant must also have a research focus in the project that will be cutting-edge in their discipline and that will contribute to the whole. Otherwise some participants may feel they are merely "in service to" the project without reaping any professional gain (see Boxes 1.3 and 1.4).

Matching Experimental Design to Goals

After the team has developed a set of goals and objectives, the next step is to formulate the project (or experimental) plan. In this phase, the team plans the overall experimental design and specifies methods for implementation, analysis, and interpretation of results. Projects that generate results to be applied in farming systems should include a plan for conveying the information to stakeholders. Depending on the type of project and the nature of the research, try to frame questions or hypotheses to guide development of the experimental plan at this stage. See Box 3.1 for examples of systems-level hypotheses.

As with all research, the experimental design must be well suited to achieving the experimental goals. This can be challenging in collaborative projects when team members lack experience in designing interdisciplinary studies that address questions at the systems level.

BOX 3.1. Examples of Systems-Level Hypotheses for Agricultural Systems Research

1. Biologically diversified agricultural systems are more resilient than less diversified systems.
2. Agricultural systems designed to reduce greenhouse gas emissions and store soil carbon will have improved soil and water quality.
3. Diverse crop and livestock systems have lower environmental and economic risk than monoculture systems.
4. All energy and nutrient needs can be generated on-farm in a New Hampshire dairy system.
5. Organic cash grain systems are economically competitive and have reduced greenhouse gas emissions per pound of grain produced compared to non-organic grain systems.

During the experimental design phase, two common problems often arise. First, if the conceptual model does not accurately represent the system, it will be difficult to develop a systems-level hypothesis or an appropriate experimental design. If the research team is having trouble at this stage, it may help to reassess the logic and assumptions behind the conceptual framework and to revisit the project goals and objectives.

Simulated agricultural systems consist of blocked and replicated treatments, generally at an agricultural research station, and are designed to answer specific systems-level questions. Existing agricultural systems consist of operations that are already in place and allow for the study of real-world systems, but with varying degrees of experimental control.

Second, differences in experimental and analytical approaches across disciplines may hinder the design process, especially if the team is composed of members who do not have experience in cross-disciplinary collaborations. If this occurs, have group members give presentations that explain their individual research approaches. These presentations should be specific to the project, describe the methods needed to address particular questions, and explain the rationale for using those methods. Taking time to exchange this information will help team members understand how other disciplines approach research and will greatly facilitate the experimental planning.

The experimental design phase generally has two planning stages. The first focuses on big-picture decisions about issues such as the research location and time frame and the types of agricultural systems and processes to be studied. Sometimes, the team will make big-picture decisions while defining the project goals and research questions.

The second stage involves decisions that are determined by the larger plan, objectives and available funding. These decisions usually focus on site selection criteria, plot size and configuration, and identification of variables to be measured.

Situating Experiments: Simulated and Existing Agricultural Systems

Two distinct approaches have generally been used to situate interdisciplinary studies of agricultural systems (Shennan et al., 1991; Drinkwater, 2002). One approach uses *simulated agricultural systems*, which are simulated, replicated experiments designed to answer specific questions. Simulated agricultural systems are often set up at agricultural research stations but can also be located on farms. The second approach uses in-place *existing agricultural systems*, systems that are already in operation for production purposes. These are more commonly used to make comparisons across specific landscapes or to understand actual systems in-situ. Existing agricultural systems can range from working farms (Drinkwater et al., 1995, Needelman et al., 1999) to larger agricultural landscapes (Auclair, 1976) and watersheds (David et al., 2009). As with other experimental decisions, choosing which type of design to use will depend on the project goals and hypotheses. Each approach has strengths and limitations.

In some cases, the appropriate research site(s) may be obvious because the questions or goals specify the design. For example, if researchers were studying the fate of legume-derived nitrogen or carbon after incorporation of green manures, they would set up a simulated, replicated system because the research would involve stable isotope tracers, which would be difficult to use on a working farm. Research on the impacts of farm-scale vegetation and crop rotation on insect pests and natural enemies would need to be conducted on existing farms due to the scale of the processes being studied.

Other questions, such as those exploring the relationship between plant species diversity and cover crop performance, could be addressed using a range of experimental designs, depending on the hypotheses to be tested. For example, research examining the effects of cover crop species composition on biomass production, weed suppression or N_2O emissions could be conducted in simulated plots at a research station. However, research evaluating cover crop performance using farmer-developed criteria such as compatibility with rotations, ease of management, and reliability would be conducted on existing farms. Frequently, a hybrid approach that includes field stations as well as working farms or landscapes may be the most effective design, because the advantages and limitations of different types of research venues are often complementary.

Historically, the simulated agricultural system model has been more widely used. Table 3.1 summarizes some of the largest and most recent replicated, on-station systems experiments in the United States comparing various production systems.

TABLE 3.1. Current Agricultural Systems Projects in the United States

PROJECT	LOCATION	DESCRIPTION
Sustainable Agriculture Farming Systems (SAFS) 1988–2002* (after 2002 merged with LTRAS)	UC Davis, Davis, CA	Initiated to produce information on sustainable farming practices, the experiment station-based project compared organic, low-input and conventional tomato farming systems in California's Sacramento Valley. The project involved a close partnership and information exchange between producers and researchers seeking to compile data most relevant and similar to commercial production.
Rodale Institute Farming Systems Trial (FST) 1981–current*	Rodale Institute, Kutztown, PA	Initiated to compare the benefits of organic agriculture over conventional agriculture, this trial takes a long-term approach to data collection and research. The project compares conventional, no-till, organic manure and organic legume treatments of corn and soybean rotations.
Agricultural Research Service Farming Systems Project 1993–current	Beltsville Agricultural Research Center, Beltsville, MD	Modeled on Rodale's FST project, this research involves five replicated cropping systems, each under three tillage options and controlled for site variation. Three organic and two conventional cropping systems are planted annually; each system differs in nutrient source, weed control and crop rotation and is managed under no-till, conventional or chisel tillage. Data are analyzed to assess the economic, agronomic, soil health, nutrient dynamic and biological sustainability of the treatments.
Long Term Research on Agricultural Systems (LTRAS) 1993–current*	Russell Ranch Sustainable Agriculture Facility, UC Davis, CA	LTRAS assesses the long-term sustainability of different crop rotations, farming systems, nitrogen inputs and levels of water use. Ten systems are studied, using rotations of tomatoes, wheat, corn, legumes, perennial grasses and alfalfa in replicated microplots.
University of Wisconsin Integrated Cropping Systems Trial (WICST) 1989–current*	UW-Madison Arlington Agricultural Research Station, southern Wisconsin	WICST provides data from three cash grain cropping systems and three forage systems in field-scale plots. Initially launched to determine if increasingly complex rotations could reduce reliance on commercial inputs, WICST has progressed to answer broader questions about sustainability using long-term data. Data on soil fertility, weed control, earthworm populations and groundwater contamination are collected from three replicated cash grain systems and three forage grain systems; there is also a focus on economic analysis of productivity.
University of Minnesota Variable Input Crop Management Systems (VICMS) 1989–current*	Southwestern Minnesota	VICMS studies the effects of four management levels on corn–soybean and corn–soybean–oat–alfalfa rotations. Management includes no inputs, lower purchased inputs, higher purchased inputs, and organic inputs. Each management/rotation combination has three replicates and is analyzed for yield, profitability and effects on soil quality.
Iowa State Long-Term Agroecological Research (LTAR) 1998–current*	Leopold Center, Ames, IA	A long-term arm of the ISU Organic Agriculture Project, LTAR is an ongoing study of the different effects of organic and conventional systems on soil quality, water quality, energy use, economic returns and weed management. The study includes four randomized rotations of corn, soybeans, alfalfa, oats, wheat and red clover. Data collected thus far have provided strong support for the environmental benefits of organic agriculture.
New Hampshire Dairy Project 2011–2015*	Organic Dairy Research Farm, Lee, NH	This four-year project focuses on sustainable livestock farming, specifically how alternative feeding crops such as warm- and cool-season grasses, summer annuals, pasture brassicas and silage affect both the environment and the quality of milk produced. In an effort to increase the sustainability of dairy operations while complying with pasture-focused FDA rules, researchers assess methane emissions, soil nitrous oxide output, overall greenhouse gas emissions, milk quality and the cost of feeding cows on these alternative pastures.
Kellogg Biological Research Station - Long Term Ecological Research (LTER) 1988–current	Hickory Corners, MI	Part of the National Network of LTER sites, the Kellogg Biological Research Station provides a space for more than 100 scientists to conduct experiments on pressing agroecological questions while contributing to national education and outreach. Many researchers work to find methods of increasing the profitability of agriculture while providing environmental benefits. Focuses include agronomy, microbial ecology, plant dynamics, insect dynamics, biogeochemistry, regionalization, ecosystem services and biofuels.
Center for Environmental Farming Systems (CEFS) 1994–current*	Goldsboro, NC	A partnership between North Carolina State University, North Carolina Agricultural and Technical State University and the North Carolina Department of Agriculture and Consumer Services, CEFS provides a physical base for research and demonstration projects at Cherry Research Farm. Field research units focus on six areas: alternative swine production, farming systems, organic systems, pasture-based beef, pasture-based dairy and small-farm production. CEFS's farming systems research unit compares five ecosystems: an integrated crop–animal system, an organically managed cropping system, a conventional cash cropping system, a successional ecosystem and a plantation forestry system.
Sustainable Cropping Systems for Dairy Farmers in the Northeast 2010–current*	State College, PA	This large-scale, multidisciplinary systems project at Penn State University compares two diverse six-year rotations that include continuous covers such as rye, canola, oats and alfalfa, interspersed with corn and soybeans. Both rotations use multiple strategies to promote sustainability and minimize off-farm inputs while producing forage, feed and fuel for a simulated 65-cow, 240-acre dairy farm.

*Denotes projects that have received SARE funding. Visit www.sare.org/project-reports to find more information about individual SARE research projects.

Simulated agricultural systems offer a number of advantages over existing agricultural systems. For one, researchers can compare management systems while reducing variability in soil type, management history, farmer skill, surrounding habitat or microclimate. Second, promising innovative cropping systems that are not currently in use by farmers can be studied. Finally, simulated systems allow for investigations over time of changes that occur after implementation of new management schemes, since all systems begin with well-defined time-zero conditions.

However, these strengths are tied to certain limitations. Since data are obtained from a single location, the effect of varying environmental conditions (e.g., soil texture or landscape-level biodiversity) on agricultural systems cannot be studied. Also, research is sometimes limited to the study of a few sets of practices to represent a given type of production system (Liebhardt et al., 1989; Temple et al., 1994), whereas in reality, farmers can choose from many variations on a central theme. It can also be challenging to achieve optimal management of all systems being compared, particularly when innovative, farmer-developed management regimes are compared to more common management systems. Even with detailed advice from farmers, farm crews may not have the skills or equipment to effectively simulate farmer practice. Furthermore, agricultural systems developed at research stations cannot adequately address landscape-scale ecosystem processes or certain socioeconomic questions. Finally, while simulated agricultural system experiments are well suited for examining early effects of management on soils, it is financially and logistically difficult to maintain these experiments over decades; thus, obtaining long-term data can be difficult.

The use of existing systems such as farms, watersheds or agricultural landscapes as study sites has been less common than the use of simulated systems, perhaps because the limitations are often thought to exceed the advantages. There is a continuing misperception among agronomists that hypotheses cannot be tested using existing sites since many factors cannot be controlled across farms. On-farm studies can be more logistically difficult due to lack of control over the research sites (for example, farmers sometimes change their plans and may forget to contact researchers). Furthermore, existing farms are usually less accessible and more dispersed, and therefore more costly to study, compared to sites at an experiment station. However, uncontrolled variation and some of the other challenges can be dealt with through appropriate research design and site selection.

The most important advantage of using existing systems as research sites is that the systems are realistic in terms of scale, management practices and farmer constraints and so provide a unique opportunity to study agricultural processes under “real world” conditions. Another advantage is that site selection can be used to either minimize or increase environmental variability to test hypotheses and achieve results that apply across a wider range of environments and conditions. For example, Needelman et al. (1999) selected farms with soil textural differences to investigate interactions between management practices and soil texture. Furthermore, *transition effects* can be avoided by selecting well-established farms with differing management regimes, which are probably closer to steady-state conditions.

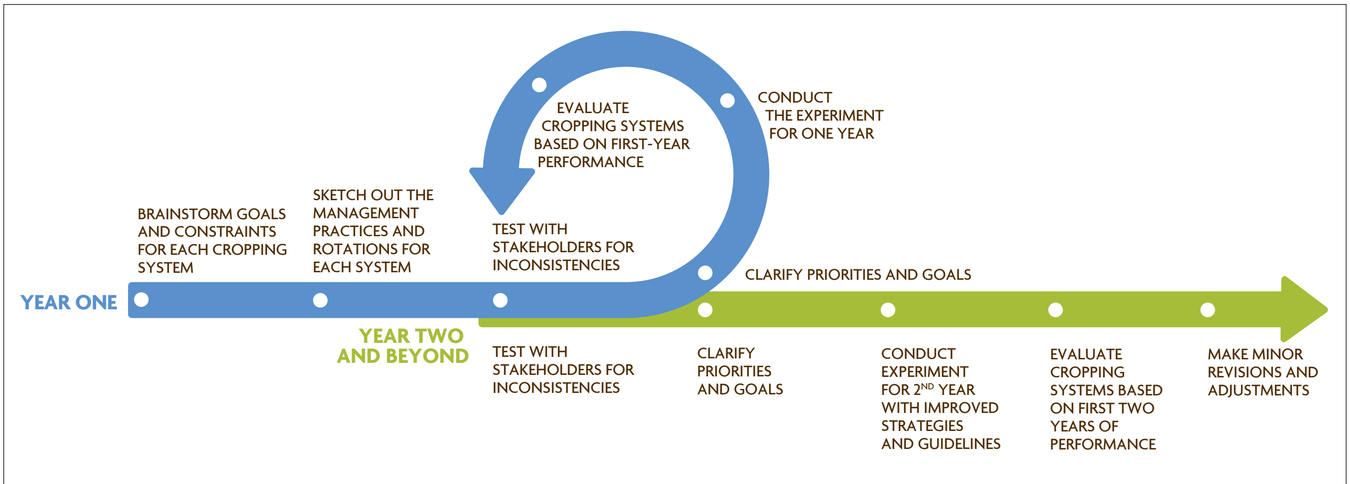
Transition Effect: An interim time period in which an agricultural system undergoes a shift from one management system to another and experiences production losses due to this shift. For example, when farmers switch from less diverse, chemical-based farming to a more biologically diverse approach with reduced inputs, they usually experience reduced yields and increased pest pressure during the first few years.

Alternatively, research that addresses changes through time can test hypotheses by using sites that have been managed for varying durations. Finally, some agricultural system properties that are influenced by landscape-scale characteristics require the use of farm-scale study sites (Letourneau et al., 1996; Elias et al., 1998), as do studies of socioeconomic processes.

Experimental Design Using Simulated Agricultural Systems

All simulated agricultural systems experiments attempt to mimic the behavior of real-world systems. To ensure that they represent viable systems from the perspective of practitioners, these experiments must be developed with grower participation. The research team needs to be clear during both the design and implementation phases about what systems are being represented in the experiment and should involve knowledgeable farmers in the design process. Moreover, when planning the research, keep in mind that any new management scheme will undergo a transition phase and will require time to reflect the current management

FIGURE 3.3. Sample Process for Developing and Refining Cropping System Treatments



This example outlines the process used to develop four organic vegetable production systems. The research team included experienced farmers and extension educators who provided a realistic assessment of the four experimental systems. (Drinkwater et al., unpublished documents from the Cornell Organic Vegetable Systems Trial).

practices. For example, if cover crop rotations are imposed on a site in which annual crops have been alternated with bare fallows, changes in the size and composition of the microbial community and labile soil organic matter (SOM) pools may be detected in two to four years while significant changes in total SOM pools may not be evident for a decade or more.

Defining the Systems

Once the goals and objectives are clearly established, defining the system treatments is fairly straightforward, as long as realistic management regimes are used. Realistic agricultural systems vary extensively, and comparisons of single management practices will not be possible in these experiments. While comparing practices by restricting the number of factors that differ across treatments can be tempting, this approach often results in failure because the treatments do not represent a viable agricultural system. The treatments being compared must be reasonable representations of agricultural systems. For example, to compare rotations with and without cover crops, other management practices must be modified to adjust for the addition of cover crops. Planting dates for cash crops will be later and nitrogen fertilizer rates can be reduced when cover crops replace bare fallows. Likewise, to compare realistic organic and conventional management systems, treatments must differ in many management practices such as crop rotation, inputs, crop varieties and planting dates. This may seem problematic to those who are more familiar with factorial designs in which all aspects of management except for the factor of interest are held constant. However, farmers can rarely make a single change in their farming system without adjusting other variables to optimize the system performance.

> "While comparing practices by restricting the number of factors that differ across treatments can be tempting, this approach often results in failure because the treatments do not represent a viable agricultural system. The treatments being compared must be reasonable representations of agricultural systems."

In order to develop specific management practices, the team must establish distinct objectives and guiding strategies for each agricultural system treatment. This approach can involve an iterative cycle in which scenarios are developed with farmer involvement, after which a wider group of stakeholders assesses whether the system treatments appear valid (Figure 3.3). Developing distinct guidelines for each treatment allows for flexibility in management practices to respond to normal variation through time, such as variability in precipitation or weed pressure, while ensuring that the management conforms to the overall strategy.

A good example of this process can be seen in a long-term systems experiment in New York comparing four

TABLE 3.2. Major Factors Determining Management Decisions for Four Organic Cropping Systems

	CS1-TYPICAL PRACTICE	CS2-INCREASED USE OF COVER CROPS	CS3-REDUCED CASH CROP INTENSITY	CS4-REDUCED TILLAGE INTENSITY
Income goal	Max income/acre	Max income/acre	Max income/hour	Max income/acre
Primary constraint	Land	Land	Labor	Land
Cropping intensity	Cash crop every year, double crops when possible	Cash crop every year, no double cropping	Cash crops alternate with a fallow year with intensive cover cropping	Cash crop every year, no double cropping
Management Priorities				
First	High soil fertility	Soil health: increased use of cover crops	Low weed pressure	Soil health: reduced tillage
Second	Weed management	Low weed pressure	Soil health: increased use of cover crops	Low weed pressure
Third	Soil health: mainly compost inputs, some use of cover crops	Reduced purchased inputs	Reduced purchased inputs	Reduced purchase inputs

Drinkwater et al. unpublished documents from the Cornell Organic Vegetable Systems Trial.

organic vegetable cropping systems. Although all of the systems focused on organic vegetable production and included crops commonly grown in the northeastern United States, their management practices reflected differences in income goals, production constraints and overall management priorities (Table 3.2). Cropping System 1 (CS1) simulated a typical, intensive vegetable system with double cropping in two of the four years (i.e., six cash crops in a four-year cycle). CS3 mimicked an innovative, reduced-intensity system developed by two experienced organic farmers and alternated one year of cash crops with one year of cover cropping, meaning cash crops were produced in two of every four years (i.e., two cash crops in a four-year cycle). CS2 and CS4 were experimental treatments developed collaboratively by the scientists, extension educators and farmers; these treatments applied key strategies used in CS3 while aiming to produce a cash crop every year (i.e., four cash crops in a four-year cycle). The goals and constraints were similar in CS2 and CS4, but CS2 emphasized the use of cover crops, whereas CS4 involved reducing tillage.

Before developing new agricultural systems experiments, review and analyze past and ongoing systems trials established across the United States (Table 3.1); each has unique design features that reflect the regional environment, farming practices and research priorities. These experiments fall along a continuum, from those investigating fundamental questions about ecological processes to those focused on optimizing regional production systems. Virtually all of these experiments can generate both practical outcomes and new knowledge of ecological processes in agricultural systems. They have also involved farmers and include supplemental experiments in addition to the main systems experiment.

So, how does the team go about developing system treatments to be compared? As with all other design decisions, begin with the goals of the research project. If the goals are to improve or optimize production systems for particular crops, then the treatments may need to capture subtle differences. For example, the project could include organic grain treatments that differ only in terms of rotation, fertility inputs and tillage. This approach is commonly used when the most important goal is to develop improvements for a management system or to evaluate a range of options in a way that is meaningful to farmers. Box 3.2 outlines how one group developed a cropping systems experiment with these goals in mind.

If the study goal is to understand how management strategies affect system processes and agronomic and environmental outcomes, then the team will want to develop system–treatments that reflect best practices for each management strategy. For example, a study could compare conventional tillage to no-till, organic to conventional, or varying levels of intensification.

If the team wants to understand how diverse, large agricultural systems function relative to managed or unmanaged ecosystems, then the study may need to include agroforestry or woody biomass treatments or unmanaged ecosystems

BOX 3.2. Using Farmer Knowledge to Explore Challenges in Potato Production Systems

In early 2001, researchers, extension staff and private crop advisers in Michigan met to address concerns among potato producers about declining yields. Farmers guessed the decreases were due to soil organic matter degradation resulting from shortened rotation sequences, minimal residue inputs and limited use of winter cover crops. Soil organic matter decline is a common problem in intensive vegetable production systems, and it is exacerbated in potato systems because growers use sandy, well-drained soils that tend to have inherently low levels of organic matter. In addition, nutrient requirements for potato production are high, often double that required by field crops.

In the study, funded by the USDA Initiative for Future Agriculture and Food Systems, farmers challenged the multidisciplinary team to provide innovative approaches that could supply sufficient nutrients to crops while protecting the environment and helping operations of different sizes remain economically viable.

The team included experts in horticulture, forage agronomy, soil science, plant pathology and agricultural economics. It met with an advisory group of growers, private crop consultants and a representative from the Michigan Potato Industry Commission. For nine months, the team reviewed the literature and farmer experience with alternative cropping systems including various rotational sequences, winter-cover alternatives and low-rate applications of compost to address soil declines in an economically viable manner.

Initially, the team designed a long-term trial that included a factorial approach to comparing low and high fertilizer nitrogen levels applied to eight potato-rotation sequences with different intensities of residues and winter cover. Potato growers, however, were not interested in this design, because it was complex and had a large number of treatments, including many that were biologically interesting but not viable in terms of farming integrity or economics. The growers were interested in an experiment that compared intact cropping systems.

As a result, the final experimental design, developed in response to input from growers and cooperative extension, was revised to compare cropping systems that included three common farmer rotations as "goal posts" to a farmer cover crop rotation that kept the soil continuously covered and produced large amounts of cover crop residues. Also included were four researcher-designed and farmer-approved alternative rotations that tested gradients of biodiversity via the presence of diverse cover crops and treatments with or without compost.

Two critical elements in this process turned out to be (1) a baseline survey to document farmer practice in pilot areas at the beginning of the project, allowing evaluation of impact and adoption over time; and (2) frequent input from the farmer advisors provided through surveys, informal discussions at the trial sites and formal meetings with the research team.

Sieglinde Snapp, Project Director

such as old fields in various stages of succession. (See Table 3.1 for examples of projects focusing on this kind of research, including the University of Michigan's Kellogg Biological Station, the US National Science Foundation's Long-Term Ecological Research Network, and the Center for Environmental Farming Systems in North Carolina.)

Design Considerations

In simulated agricultural research projects, several aspects of design differ from typical replicated plot experiments. Three issues deserve special attention: plot size, management regimes within treatments, and the use of supplemental, small-scale experiments.

Plot Size

Systems experiments usually require much larger plots than typical experiment station plots, partly to accommodate farm-scale equipment. Using farm-scale equipment offers two main advantages: (1) farmers tend to view results more favorably if the system treatments are managed with the equipment they will be using, and (2) it enables researchers to run accurate energy and economic analyses. Moreover, plot size has important consequences for the experiment itself. Larger plots reduce the significance of edge effects—the influence of differences in microclimate and weed pressure along field margins—and tillage impacts, both of which can become more problematic over time. Large plots ensure that there is plenty of space for sample collection by multiple lab groups, or for experiments to be embedded in the main plots. For example, in long-term experiments, weed pressure can be exacerbated by species that mature and produce seeds along plot edges. In addition, any study that includes research on highly mobile organisms (e.g., arthropods) will require very large plots, and in some cases adequate space is not available. For example, some characteristics of arthropod communities can only be studied using real farm sites because simulated systems cannot be made large enough to mimic on-farm conditions. Likewise, moldboard plowing in small plots can result in poor seed-bed preparation and dead furrows. Excessive wheel traffic can also be a problem in small plots. The team will need to weigh the costs of maintaining a larger experiment against the benefits of larger plots. For example, large plots can be impractical if the study crops are expensive to grow and harvest (such as vegetables that are sequentially hand harvested).

Management Regimes

In traditional factorial experiments, the same crops are grown at the same time. Researchers seek to eliminate crop species as a source of variability so they can study other factors such as tillage or fertility management. In many agricultural systems projects, even those designed as replicated systems comparisons, the treatments being compared most likely will have different crop rotations, and the same crops might not be grown in the same year. During design, remember that crop species is just one of many factors that affect the overall performance of a system. In a systems experiment, the entire system, including the treatments, is the unit of study.

There are two ways to create rotations for each system:

- *Accept rotational differences as a factor distinguishing the system treatments.* If the goal is to replicate and understand distinct cropping systems, then it might not be necessary to emphasize the performance of specific crops across the systems. Often, these differences in rotation are essential for defining systems that make sense from a farming perspective. For example, a major difference between organic and conventional systems is rotational sequence, because organic systems rely on rotation as part of pest management, whereas conventional systems have access to inputs such as fertilizers and pesticides. If the plan is to grow different crops each year, consider using economic assessments to compare the performance of system treatments (e.g., the cost of production relative to yields and crop value), or consider comparing yields relative to county averages (e.g., "Yields were 10 percent above and 20 percent below county averages in cropping systems 1 and 2, respectively"). The study could also compare soil properties and other attributes to the stage of crop development (e.g., soil health properties can be compared six weeks after planting or at crop senescence). Finally, the results for a particular year become less important as the experiment continues, because trends can be analyzed over time and from multiyear averages of crop-related data. For instance, after 10 years of data collection, a team can examine yield trends over time, so rotational differences across the treatments become less important.
- *Design the experiment to accommodate rotational differences and allow for comparison of crops in the same growing season.* Rotations can be designed so that the same crop will occur at certain points in the rotation. For example, the team could design three-year and six-year rotations so that corn occurs in the same growing season at least once per rotation cycle. A split-plot design provides the strongest approach to allowing for rotational differences while maximizing opportunities to compare crops because it can accommodate different entry points for each cropping system (Peterson et al., 1999). The

Split Plot. In a split-plot experiment, there are two levels of experimental units: whole plots, and split plots (subplots) within these plots. Split plots allow for an additional variable to be tested within the main experiment. Randomization is used for both the whole plot and the subplots.

FIGURE 3.4. Randomized Complete Block Split-Plot Design for Farming Systems Project (FSP) at Beltsville Agricultural Research Center, Maryland

CT	101	r/SB/w	Org6	201	A2	Org3	301	v/C/r	Org6	401	A3
	102	W/SB		202	A3		302	r/SB/w		402	A2
NT	103	r/SB/w		203	A1		303	W/F/v	NT	403	C/r
	104	W/SB		204	W/F/a	NT	304	W/SB	CT	404	C/r
Org2	105	v/C/r		205	a/C/r		305	r/SB/w		405	W/SB
	106	r/SB/v		206	r/SB/w		306	C/r		406	r/SB/w
Org6	107	W/F/a	Org2	207	v/C/r	Org6	307	A2	NT	407	r/SB/w
	108	A1		208	r/SB/v		308	r/SB/w		408	W/SB
	109	a/C/r	Org3	209	v/C/r		309	A1	Org3	409	W/F/v
	110	r/SB/w		210	W/F/v		310	a/C/r		410	v/C/r
	111	A3		211	r/SB/w		311	W/F/a		411	r/SB/w
	112	A2	CT	212	W/SB		312	A3	Org6	412	a/C/r
Org3	113	r/SB/w		213	r/SB/w	CT	313	C/r		413	W/F/a
	114	W/F/v		214	C/r		314	r/SB/w		414	A1
	115	v/C/r	NT	215	C/r		315	W/SB		415	r/SB/w
CT	116	C/r		216	r/SB/w	Org2	316	r/SB/v	Org2	416	v/C/r
NT	117	C/r		217	W/SB		317	v/C/r		417	r/SB/v

SYSTEM DESCRIPTIONS

SYSTEM	YEARS IN ROTATION	ROTATION	NUTRIENTS	WEED MANAGEMENT
No Till (NT)	3	C-SB-W/SB	Synthetic	Herbicide
Chisel Till (CT)	3	C-SB-W/SB	Synthetic	Herbicide
Organic (Org2)	2	C-SB	Legume + animal manure	Cultural
Organic (Org3)	3	C-SB-W	Legume + animal manure	Cultural
Organic (Org6)	6	C-SB-W-A-A-A	Legume + animal manure	Cultural

The Farming Systems Project (FSP) uses a split-plot design with cropping system as the main plot and rotation entry point as the split plot, so within a given cropping system all crops in the rotation are present each year. A = alfalfa interseeded with triticale each fall; C = corn; SB = soybean full season; W/SB = wheat–soybean, double crop; W/F = wheat, fallow; O = spring oats; v = vetch; r = rye. Capital letters indicate crops harvested in 2014. Lower-case letters indicate cover crops or crops planted but not harvested in 2014. Numbers (101 to 417) identify each plot. NOTE: This figure has been amended for publication and does not represent the scale or physical layout of FSP plots. Adapted from Cavigelli et al. (2005).

number of split plots is determined by the length of the rotation cycle, so that the entire rotation is represented in any given year (Figure 3.4). The use of split plots to represent each entry point in the rotation is an extremely effective design that strengthens the power of the experiment to detect management and/or climate interactions and to directly compare crop performance within management regimes; however, it greatly expands the size and complexity of the experiment. Several cropping systems studies have taken an intermediate approach, using a split-plot design to accommodate more than one point in the rotation each year (usually two to three) without representing the entire rotation every year.

Supplemental Satellite Experiments and Nested Subplots

Many agricultural systems experiments include smaller experiments located outside and/or inside the main plots to test new management practices or to solve management problems occurring in the main experiment. Smaller experiments ("satellite trials") outside of the main plots often consist of small factorial trials intended to solve a problem or test new equipment. These short-term, quick assessments can pretest new varieties, planting densities or techniques for incorporating cover crops. Satellite trials do not account for all variables operating within the larger experiment, but by using them to screen practices, the team can improve management while reducing risks to the main experiment.

Subplots embedded within the larger experiment can be used to test hypotheses and are effective for teasing out underlying mechanistic differences across the systems. When using embedded subplots, only one factor is varied so that specific cause-and-effect relationships within the management system can be investigated. For example, small, paired plots could be used to determine whether weed pressure affects crop yields. Treatments could include a plot in which weeds missed by the normal weed control practices are removed by hand and a "control" plot in which ambient weeds are not removed. (See p. 63 in chapter 4 for a specific discussion of the use of subplots.)

Long-Term Experiments

Many ecosystem processes, particularly those related to soil organic matter dynamics, cannot be adequately studied in less than a decade. To produce useful information, simulated agricultural system studies need to go through two to three rotation cycles, which requires a minimum of 10 to 12 years. Results from the first rotation cycle often represent a transitional phase and do not generally reflect the potential performance of a newly established system.

For long-term studies, establish methods for archiving research protocols, samples and data. Develop a master document to archive field notes and descriptions of weather, field operations and sample collection, along with any observations of unique factors that may have influenced system performance. These may include variables such as weather patterns that interfered with management operations or crop growth. Also document any deviations in management or errors in operations for specific plots. If not adequately catalogued, these events may be lost to future researchers who are trying to make sense of archived data. Also include a system for updating the agricultural practices to keep the experiment relevant (Aref and Wander, 1997). Finally, have a mechanism for maintaining continuity of management regimes, sample collection, analytical techniques and storage methods so that consistency does not depend on a single technician or graduate student. Identify at least one person, usually the team leader, who will commit to keeping the data and archived samples organized and accessible so that the research can continue to build on the early findings of the experiment.

Experimental Design Using Existing Agricultural Systems

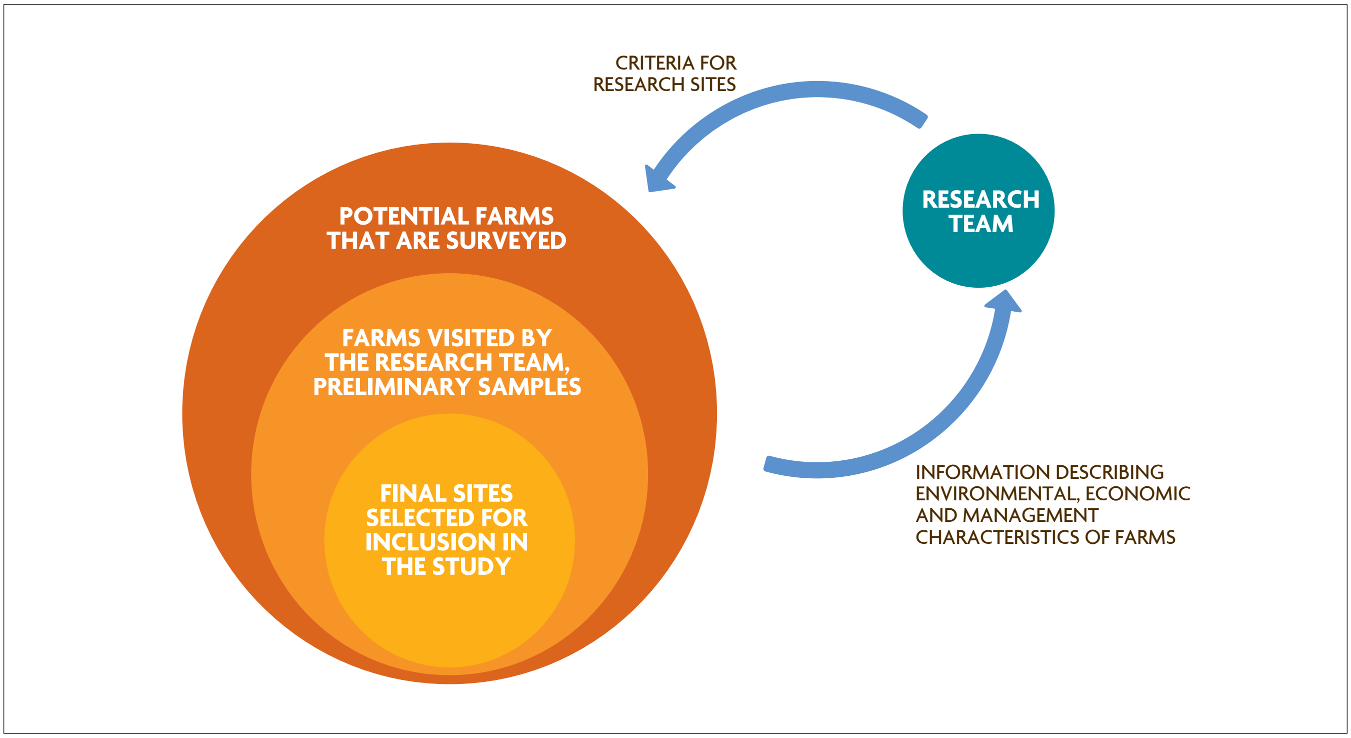
As with simulated research sites, the most suitable sites for existing agricultural systems will be determined from the research goals. Examples of where existing sites may be better than simulated sites for systems research include:

- Farm-scale questions, particularly those relating to effects of farm-scale vegetation or land use, farmer decision-making, marketing strategies and farm enterprise budgets
- Studies in which cross-scale interactions may be important. This is generally the case for research involving integrated pest management or organic farming systems where natural biological control is an important line of defense
- Research targeting processes that operate at scales too large to be accommodated by research stations, such as economics and other social system processes, questions focused on highly mobile pests or beneficial insects, and landscape-level ecological processes
- Research on interactions between environmental variation (e.g., soil type, texture or topographical location) and management
- Research aimed at improving management practices that require unique expertise or equipment not available at the research station
- Studies of innovative systems located on private land and that would require time, money or new skills to recreate at experiment stations.

Site selection is usually an iterative process that alternates between information gathering and decision-making (Figure 3.5). As the team explores sites, the experimental plan may need to be adapted to make it compatible with available sites. Although study sites may be identified during proposal writing (since site selection often requires preliminary data collection), make the final site choices after funding is secured.

The most important consideration when choosing existing agricultural systems study sites is to minimize confounding variables across farms; however, these variables depend on the questions being addressed. For example, when studying how management practices affect soil properties, the farm location and the adjacent land use or vegetation may not be important, but parent soil type and prior uses would be critically important. In contrast, when studying aboveground arthropod communities across farms, the surrounding habitat, microclimate and field size all need to be considered. Not surprisingly, as the number of disciplines involved in the study increases, the list of confounding variables becomes longer, and it becomes more challenging to select sites that do not have confounding variation.

FIGURE 3.5. Nested Site Selection



The nested approach uses surveys to collect information from a large pool of potential farms and then narrows down the possible sites based on criteria developed by the research team.

Although there is no single "correct" process for identifying farm sites, the following key steps are broadly applicable:

- Familiarize all team members with the literature from on-farm agricultural systems research before beginning the site-selection process.
- Define and prioritize the site-selection criteria: location, scale, crops, soil type, management strategy, etc.
- Conduct a preliminary survey of potential study sites to obtain basic knowledge of the common characteristics of these farms. Consult with growers with whom team members have established relationships.
- If the study requires a large number of farm sites, consider identifying more potential sites than needed, and then collect basic information after finalizing the selection criteria. Extra site surveys can be useful for providing a larger context for the study.
- Consider conducting site visits as a group. Some groups find it efficient to visit sites after they have narrowed the list down to probable study locations. Final site selections should be made after these visits.
- Consider including preliminary soil tests or other diagnostic measurements (e.g., presence or absence of pests or beneficial insects) as additional information for the final site selection.
- When finalizing selections, include extra sites to allow for the possibility that some farms may be eliminated as the study progresses (the farmer's plans may change, sites may be lost through crop failure, etc.).
- Select farm sites where growers are enthusiastic about the research project or have a track record of hosting research on their farms. This is particularly important when the project will be manipulating the system or the farmer will be asked to make special accommodations for the research.
- Compensate growers appropriately for their participation in the research, and include a plan for sharing the research findings with all cooperating farmers.

Box 3.3 describes the extensive farm-site selection processes used for a project comparing ecological characteristics among a large number of farms.

BOX 3.3. Site-Selection Process for Comparing Groups of Farms with Distinct Management Systems

The goal of this team-led study, funded by SARE, was to test hypotheses about the impacts of management on ecological and agronomic characteristics in conventional and organic production systems. The team developed interdisciplinary hypotheses and an experimental design that addressed interactions among components of the systems (Drinkwater et al., 1995). In addition, each investigator had a focused, discipline-specific hypothesis about soil processes, crop production, plant pathology or arthropod community dynamics, which supported the study's overall goals (Workneh and van Bruggen, 1994; Letourneau and Goldstein, 2001).

After agreeing on the major questions, the team began the process of site selection by listing all the criteria representing all the disciplinary perspectives. While the list highlighted differences in priorities, the team agreed to maximize overlap in geographic location, local climate and parent soil types between both types of farming systems. It also produced a list of secondary criteria consisting of attributes that at least some of the sites needed to contain.

Initially, the team considered two important vegetable-producing regions as potential study areas: the Central Coast valleys of California, which produce mainly cool-season vegetables; and the inland Central Valley, which produces warm-season vegetables. The team used site visits and a questionnaire to gather information on organic and conventional vegetable producers in both regions. The coastal region had favorable characteristics for some of the project's objectives; most notably, a potentially serious root pathogen of lettuce was present on both types of farms. However, several obstacles made the Central Coast region problematic for this interdisciplinary study. Specifically, the organic and conventional farms were segregated into different valleys and had almost no geographical overlap. In addition, the very short duration of lettuce crops (six weeks) made data collection at many field sites impossible.

In contrast, in the Central Valley, organic and conventional farms overlapped in their geographical distribution, and although there was a climatic gradient, both types of farms were located along the gradient. Furthermore, all of the organic farms had conventional agricultural neighbors, and some were surrounded by large conventionally farmed fields. As a result, the team chose tomato production in the Central Valley for the project. In contrast, if the team's plant pathologist had been conducting the research alone, she would have opted to study lettuce production in the Central Coast region.

Once the team selected the region and the crop to be studied, it needed to select farms as study sites. This process required compromise among disciplines. Each team member ranked sites by priorities related to their area of expertise. In this way, the sites that were most important for each discipline were sampled by the entire team, providing a strong basis for developing integrated questions. Because there was a limited number of organic farms, the team first selected organic farm sites and then identified an appropriate mix of comparable conventional farms. The team originally planned to pair sites even though they expected to use multivariate statistics, but in the end, they were not able to arrange the sites in pairs that were acceptable to all disciplines.

In the first year, in addition to farm sites that were sampled by all disciplines, individual researchers chose and sampled extra sites to strengthen their own disciplinary work. At the time, this seemed like a realistic compromise because it allowed the group to take an integrated interdisciplinary approach on a majority of sites while also providing some autonomy to more rigorously test sampling methods and selection criteria for each research component. At the end of the first year, however, the group discovered that the findings from the sites that were sampled by all disciplines were much more interesting and informative. In the second year, the group agreed on a set of 18 sites that were the best for integrated questions, and these were sampled by all disciplines.

See Drinkwater et al., 1995, for more details.

Design Considerations

Along with site selection possibilities, multiple types of systems can be studied when using existing systems. The following examples offer insight into how to match methodology with research goals.

Comparing Farm Pairs

Comparing farm pairs is the most common method used to study working farm systems. It assumes that confounding variation can be reduced by carefully matching paired farm sites. This design considers each pair as a replication, which allows common statistical analyses to be used (Lockeretz et al., 1981; Reganold, 1993). The strategy works fairly well if the study involves fewer disciplines and the geographic distribution of the farm types to be compared is similar. As the number of disciplines involved in the study increases, agreeing on how to designate farm pairs can become difficult because the number of criteria used to match the pairs also grows. For example, soil type would be the most important criteria for matching farms in a study focusing on the impact of tillage intensity on soil properties. In contrast, soil type, field size, microclimate and surrounding landscapes would all need to be matched to examine the impact of farming systems on soil processes and arthropod pests. Furthermore, if the farm types are geographically segregated or differ by landscape position or soil type, establishing farm pairs without confounding environmental variability will not be possible.

Comparing Groups of Farms

When pairing farms is not possible, another option is to design the study to compare groups of farms using multivariate statistics (Drinkwater et al., 1995; Wander and Bollero, 1999). This approach allows greater flexibility in site selection because the need to find farm pairs that meet matching criteria is eliminated. Instead, the criteria are applied to groups of farms. Farm sites are selected so that confounding variables have similar distributions in each group. For example, groups of farms are usually defined in terms of specific environmental variables (Needelman et al., 1999) or management types (Drinkwater et al., 1995) and are then compared to address the question of interest. A variation on this approach is to identify a set of farms that form a continuum (in terms of environmental or management characteristics) rather than contrasting groups (Steenwerth et al., 2002). For example, the use of a chronosequence—a set of soils, farms or ecosystems that have been under differing management regimes for a varying length of time—can provide useful information about how quickly the agricultural system responds to changes in management.

In-Depth Study of a Single Site or a Single Pair of (Usually Adjacent) Farms

Farms can serve as sites for mechanistic studies of small-scale processes such as microbially mediated processes. In this case, rather than focus on the effects of management practices on ecosystem processes, researchers concentrate on interactions within a farming system that is already well characterized by previous research (Steinheimer et al., 1998).

Larger-Scale Studies

Systems projects often address questions about processes that occur at scales larger than a field or farm. Examples include watershed comparisons (Sovell et al., 2000; Napier and Tucker, 2001) or studies that examine how land management varies across regions or through time (Auclair, 1976; Donner, 2003).

Mother-Baby Trials

This hybrid method combines the use of existing farm sites and experimental research station plots to systematically link biological performance with farmer assessment of technologies (Snapp et al., 2002). This approach is extremely powerful for developing improved management options, and it allows researchers to evaluate a wide variety of management strategies across varying farm environments and in a replicated field station design in a single experiment. It is also appealing to farmers because they can choose the options most relevant to their operation after viewing trials at the research station. A systematic framework to guide this approach was developed by Snapp et al. (2002) to evaluate soil fertility management options available to smallholder farmers in Malawi. The study, using replicated experiments at research stations, included all fertility management options and investigated ecological mechanisms and outcomes; farmers then selected a subset of these options, usually three or fewer, to test in their own fields under realistic conditions.

Case Studies

Case studies are useful when in-depth, qualitative information is needed. The social sciences rely more heavily on this approach than other disciplines, but case studies have also been proven useful in providing a holistic overview of specific farms. In fact, case studies can be excellent educational tools because stories are effective for reaching diverse audiences (Mikkelsen, 1995) and for enlightening agricultural researchers about management systems they rarely encounter. Case studies can also serve as the basis for generating hypotheses and can lead to new discoveries about how particular management systems function on working farms. The SARE case study on p. 58 provides an in-depth example of how one researcher used qualitative methods to holistically evaluate the decision-making process at three very different dairy systems in rural Wisconsin.

Design Considerations for Statistical Models

In general, systems-based studies and factorial experiments confront similar issues when determining the number of replications and plot configurations needed for adequate statistical analyses. A few issues, however, are specific to agricultural systems research and can be addressed by the experimental design and sampling strategies.

To start, what constitutes a "control" for a systems experiment? In factorial experiments, scientists often strengthen the design by including a control plot that does not receive the treatment (for example, in a fertilizer experiment, the zero-nitrogen treatment is the control). In a systems study, however, this type of control does not usually make sense, and there is generally no straightforward way to define a standard control treatment. Some studies do include a "reference" system, which often consists of the "typical" or "conventional" management system, to compare with a number of experimental alternatives. Depending on the experiment, this system may be referred to as "conventional" or "farmer practice." This is more accurate than referring to the system as a "control," since for most agricultural systems studies, the "control" can vary depending on the researchers' perspectives. In experiments comparing agricultural systems to native or unmanaged native systems, the native ecosystems could be considered "controls" compared to agriculture. In general, avoid designating one system as a "control" because that determination is largely subjective in systems experiments and can lead to confusion.

Spatial variability can also be an issue in systems experiments because of the larger plot sizes. To minimize the impact of unexpected spatial variability in on-farm studies, research can be carried out within smaller, defined field plots (Drinkwater et al., 1995; Schipanski et al., 2010). Farmers, who are usually knowledgeable about spatial variability in their fields, can point out areas that behave differently and should be avoided. Within very large fields, smaller research plots can be used to target particular soil types to allow for better control of soil variability across sites. In field station experiments, allocate resources (e.g., time, funds) for a spatial assessment of the site if it is relatively large. A "uniformity trial" can be done by planting a single crop across the entire experimental site and collecting soil samples and plant biomass data on a defined grid. These baseline studies can be conducted for several years. GPS can be used to identify sampling locations, and geostatistical techniques can characterize spatial variability. Cavigelli et al. (2005) present an excellent example of this technique.

When considering how to block an experiment, analyses of spatial variability can be particularly useful. If possible, arrange blocks to reflect soil variability. Preliminary assessment of the research site has the added advantage of providing a framework that can be used for future sampling and to establish a strong baseline. As the experiment progresses, researchers can document changes over time by sampling a subset of points that were characterized during the preliminary assessment.

Because systems experiments tend to focus on longer-term trends and changes over time, establish a well-documented time-zero baseline, particularly for simulated, replicated system studies, to strengthen the ability to make these assessments. Cropping systems experiments in which the site is repeatedly planted to a single crop often begin with two to three baselines or year zeros. Allow multiple years for baseline data collection if the site includes fields with different management histories that have been combined for the experiment. Careful time-zero sample collection and archiving can also greatly expand future research possibilities. For example, consider collecting and archiving air-dried samples and freezing small samples (ideally at –80°C) in case there is a future interest in using molecular or other techniques.

Financial Planning

Start planning for the financial support of systems projects early. Most simulated agricultural systems projects that have been in place for 10 or more years are still in operation because the researchers planned ahead to receive institutional support (Table 3.1). Even where institutional support is provided, extramural funding is often required to carry out more ambitious research efforts after the experiment has been established. Interdisciplinary systems projects can be initiated with funding from competitive grants, but do not expect to maintain these studies beyond about eight years with competitive grant funding alone. This part of this chapter focuses on financial planning for initiating an interdisciplinary systems research project. Strategies for long-term funding are discussed further in chapter 5.

Financial planning for interdisciplinary systems experiments can be complicated if the project includes more than three or four co-principal investigators (co-PIs) from different institutions, and if the goals are long term and exceed typical funding cycles. For large, complex projects, identify multiple funding sources in the early stages of project development if possible. Discuss funding levels early in the process so that proposal goals and objectives that are set for a particular proposal will be realistic for the funder.

Two considerations shape the distribution of funds among collaborators and institutions: (1) good collaboration will be promoted if funds are reasonably distributed among the individuals and institutions playing major roles in the project; and (2) the proposal goals, objectives and work plan must be compatible with the mission and goals outlined in the request for proposals. Budget planning typically needs to begin earlier for interdisciplinary projects than for disciplinary research. In single-discipline studies, researchers often develop the goals and experimental plan before constructing the budget because they have the experience to estimate the resources required for the planned work. This is often not the case in longer-term interdisciplinary systems projects; begin budget planning early, and be willing to refine and adjust the budget over time.

As with many other aspects of project planning, budget development is an iterative process that often requires adjustment of the experimental plan. The following steps can help with budget planning:

- Identify a target budget that is reasonable for the likely funding source and that reflects the project scope. Have this discussion in the early planning stages to help avoid developing unrealistic goals. Nothing will cause conflict in a newly formed group faster than trying to shrink a $600,000 research plan to meet a $200,000 budget cap. Begin with a conservative list of objectives and an experimental plan that can be expanded if the total budget is larger than expected.
- As goals and objectives become finalized, identify who will do the work to achieve each objective.
- The project leader should take a first stab at assigning budget allocations to organizations and co-PIs based on the outcomes expected from each contributor. Then, ask each co-PI to aim for those amounts when they draft their budgets. If funding sources allow indirect costs, be sure to include these in the budget plan and be clear about where overhead will be charged.
- While the experimental plan is being developed, have each organization and PI draft an individual budget. This will help in defining the details of the work plan. For example, the preliminary experimental plan may specify that 25 farms will be studied, but the budget may only allow for 20 farms.
- As the team fine-tunes the budgets and work plan, continue to assess whether the integrity of the overall project is being maintained. The project leader must help the group balance individual interests and budget needs with the needs of the project as a whole. Often, the original plan developed by an interdisciplinary team is too costly and needs to be paired down to meet budget limitations. This can be an advantage, because it helps the group to focus and identify key priorities.

This open budgeting process ensures that experimental planning and budget development progress concurrently with the participation of all collaborators. As with any large project, establish a shared budget that is explicitly set aside for expenses related to the overall project. Collaborative research often entails foundational costs, which cannot be attributed to a single co-PI but are needed for the overall enterprise. In simulated agricultural system experiments, foundational costs would include land-use fees, farming costs (including spatial analyses and baseline years), and data collection (e.g., yield and biomass data, soil characterization). Create a detailed expense budget to help ensure that resources will be available to maintain the project infrastructure, including costs for travel, conference calls or video conferencing. If necessary, budget for administrative assistance to manage the project.

Specify foundational costs to help achieve a reasonable balance between resources used to maintain experimental plots and resources used for data collection. A project in which 80 percent of the resources go toward maintaining experimental plots is probably not viable unless there is a solid plan for obtaining other funds to perform the research. Likewise, if performing an on-farm study, budget for costs associated with characterizing the research sites through farmer interviews and preliminary sampling. In contrast to field station experiments, which have ongoing farming and plot maintenance costs, foundational costs for on-farm research decrease after the research sites are characterized. In both cases, consider generating supplemental funding by adding disciplinary research that capitalizes on the established infrastructure. Regardless of the long-term strategy, give careful thought to support for the project infrastructure in the planning stage to facilitate collaborative aspects of the project during the implementation phase.

Look for opportunities to reduce costs by sharing items such as research vehicles, basic soil characterization data and analytical services. For research in both simulated and existing agricultural systems, sharing information and collecting samples that can be used by multiple laboratories can also result in significant savings.

Above all, ensure that the budgeting process is fair and transparent. Give special consideration to untenured faculty to ensure they receive adequate funding to continue meeting their tenure goals. Since individuals from nonprofit organizations often lack permanent funding and are totally dependent on grants, they might need to receive compensation to participate in the project, as will farmers. Such compensation normally includes the costs of staff time needed for the project. Be sure everyone on the research team understands these considerations.

SARE CASE STUDY Socioeconomic Analysis of Organic, Grass-Based and Conventional Dairy Farmers in Wisconsin: Using Quantitative and Qualitative Methods to Study Farmer Decision-Making

Photos courtesy of Caroline Brock

Systems-based research projects often involve a research team tackling a topic from a variety of disciplinary perspectives, with a strong focus on collecting quantitative data. But that doesn't mean that a solo investigator can't take on rigorous systems research involving more qualitative approaches.

In Wisconsin, SARE-funded doctoral student Caroline Brock did just that, conducting an in-depth study on structural divergence in the dairy sector and farm decision-making related to systems adoption. In her thesis, published in 2010, she used a combination of quantitative survey data and qualitative, in-depth interviews to explore how organic, Amish and conventional dairy farmers in Wisconsin made decisions about which types of farming system they would adopt.

One early challenge facing Brock, given that Wisconsin has over 10,000 dairy farms, was creating system boundaries. She focused on large-scale conventional, mid-sized conventional, management-intensive rotational grazing (MIRG) and organic systems. This choice was partly based on her analysis of data from an extensive state-wide survey of dairy farmers performed in 2003 and 2004. The survey showed that the state's dairy sector had undergone significant structural divergence in terms of size and management systems during the previous 25 years. In particular, larger confinement dairy operations, organic and MIRG systems had become more important. In addition, a growing number of Amish families were operating dairy farms, making them important on the Wisconsin farm landscape. Brock's "take-off point" was that "Wisconsin farming systems' divergence is an expression of farm household decision-making," she said, and she wanted to better understand the complex forces that shaped those decisions.

To do that, she used the survey data and other sources to identify 60 dairy farmers willing to sit down for an extensive, structured interview about farm decision-making. Brock noted that the approach was motivated in part by the common-sense observation that these farming choices involve both lifestyle and financial considerations.

The combination of statistical data and wide-ranging interviews opened a revealing window into the complex forces shaping farm family choices. In particular, Brock found that concepts called "oikonomia" and "bounded rationality" helped explain dairy farmer decisions.

"Oikonomia is an integrated approach to decision-making that stems from the origins of the word *economics*—oikos, which translates as household. Oikonomia incorporates social, spiritual and ecological as well as economic dimensions." Brock wrote in her thesis. One focus was on why farmers chose or declined to adopt organic systems. She targeted her study on "pasture-based and smaller conventional farmers as they may be the most likely to adopt organic practices."

"Farming systems choices are, in fact, fundamental lifestyle choices, especially for the modest-sized operations of southwestern Wisconsin, where the family contributes the majority of the labor and spends most of their time as a family on their farm," she said. "It is the integrated essence of the family-farm experience, where work, consumption, leisure, relationship to others, the environment and spirituality all occur largely in the same place."

For instance, she found that Amish farmers' spiritual or cultural beliefs might lead them to make different choices about adopting specific dairy practices compared to those made by a non-Amish farmer facing similar issues. She also found that the concept of bounded rationality was useful for incorporating the idea of internal and external constraints, which may deter decision-makers from fully living out these oikonomia values.

References

Aref, S., and M.M. Wander. 1997. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the Morrow Plots. *Advances in Agronomy* 62: 153–197.

Auclair, A.N. 1976. Ecological factors in the development of intensive management ecosystems in the midwestern USA. *Ecology* 57: 431–444.

Balasubramanian, V., B. Alves, M. Aulakh, M. Bekunda, Z. Cai, L. Drinkwater, D. Mugendi, C. van Kessel, and O. Oenema. 2004. Crop, Environmental, and Management Factors Affecting Nitrogen Use Efficiency. In *Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*, ed A.R. Mosier, K. Syers, and J.R. Freney. pp. 19–33 The Scientific Committee on Problems of the Environment (SCOPE), Island Press: Washington, DC.

Cavigelli, M.A., L.L. Lengnick, J.S. Buyer, D. Fravel, Z. Handoo, G. McCarty, P. Millner, L. Sikora, S. Wright, B. Vinyard, and M. Rabenhorst. 2005. Landscape level variation in soil resources and microbial properties in a no-till corn field. *Applied Soil Ecology* 29: 99–123.

David, M.B., S.J. Del Grosso, X.T. Hu, E.P. Marshall, G.F. McIsaac, W.J. Parton, C. Tonitto, and M.A. Youssef. 2009. Modeling denitrification in a tile-drained, corn and soybean agroecosystem of Illinois, USA. *Biogeochemistry* 93: 7–30.

Donner, S. 2003. The impact of cropland cover on river nutrient levels in the Mississippi River Basin. *Global Ecology and Biogeography* 12: 341–355.

Drinkwater, L.E. 2002. Cropping systems research: reconsidering agricultural experimental approaches. *HortTechnology* 12(3): 355–361.

Drinkwater, L.E., D.K. Letourneau, F. Workneh, A.H.C. Van Bruggen, and C. Shennan. 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. *Ecological Applications* 5: 1098–1112.

Elias, E., S. Morse, and D.G.R. Belshaw. 1998 Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia. *Agriculture, Ecosystems and Environment* 71: 93–113.

Friedland, A.J., and C.L. Folt. 2000. *Writing Successful Science Proposals*. Yale University Press: New Haven, CT.

Heemskerk, M., K. Wilson, and M. Pavao-Zuckerman. 2003. Conceptual models as tools for communication across disciplines. *Conservation Ecology* 7(3): 8.

Letourneau, D.K., and B. Goldstein. 2001. Pest damage and arthropod community structure in organic vs. conventional tomato production in California. *Journal of Applied Ecology* 38(3): 557–570.

Letourneau, D.K., L.E. Drinkwater, and C. Shennan. 1996. Soil management effects on crop quality and insect damage in commercial organic and conventional tomato fields. *Agriculture, Ecosystems and Environment* 57: 179– 187.

Liebhardt, W.C., R.W. Andrews, M.N. Culik, R.R. Harwood, R. R. Janke, J. K. Radke, and S.L. Rieger-Schwartz. 1989. Crop production during conversion from conventional to low-input methods. *Agronomy Journal* 81: 150–159.

Lockeretz, W., G. Shearer, and D.H. Kohl. 1981. Organic farming in the Corn Belt. *Science* 211: 540–547.

Mikkelsen. R.L. 1995. Swine waste disposal dilemma: a case study. *Journal of Natural Resources and Life Sciences Education* 24: 169–172.

Napier, T.L., and M. Tucker. 2001. Use of soil and water protection practices among farmers in three Midwest watersheds. *Environmental Management* 27: 269–279.

Needelman, B.A., M.M. Wander, G.A. Bollero, C.W. Boast, G.K. Sims, and D.G. Bullock. 1999. Interaction of tillage and soil texture: biologically active soil organic matter in Illinois. *Soil Science Society of America Journal* 63: 1326–1334.

Palm, C.A., P.L.O.A. Machado, T. Mahmood, J. Melillo, S.T. Murrell, J. Nyamangara, M. Scholes, E. Sisworo, J.E. Olesen, J. Pender, J. Stewart, and J.N. Galloway. 2004. Societal Responses for Addressing Nitrogen Fertilizer Needs: Balancing Food Production and Environmental Concerns. In *Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*, ed A.R. Mosier, K. Syers, and J.R. Freney. pp. 71–92. The Scientific Committee on Problems of the Environment (SCOPE), Island Press: Washington, DC.

Peoples, M.B., E.W. Boyer, K.W.T. Goulding, P. Heffer, V. A. Ochwoh, B. Vanlauwe, S. Wood, K. Yagi, and O. Van Cleemput. 2004. Pathways of Nitrogen Loss and Their Impacts on Human Health and the Environment. In *Agriculture and the Nitrogen: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*, ed A.R. Mosier, K. Syers, and J.R. Freney. pp. 53–70. The Scientific Committee on Problems of the Environment (SCOPE), Washington, DC.

Peterson, C., L.E. Drinkwater, and P. Wagoner. 1999. Farming Systems Trial. Rodale Institute: Kutztown, PA.

Reganold, J.P., A.S. Palmer, J.C. Lockhart, and A.N. Macgregor. 1993. Soil quality and financial performance of biodynamic and conventional farms. *Science* 260: 344–349.

Schipanski, M.E., L.E. Drinkwater, and M.P. Russelle. 2010. Understanding the variability in soybean nitrogen fixation across agroecosystems. *Plant and Soil* 329: 379–397.

Shennan, C., L.E. Drinkwater, A.H.C. van Bruggen, D.K. Letourneau, and F. Workneh. 1991. Comparative Study of Organic and Conventional Tomato Production Systems: An Approach to On-Farm Research. In *Alternative Agriculture*, part 2, ed. J.P. Madden. pp. 109–32. National Academy Press: Washington, DC.

Snapp, S., P.G. Kanyama, B. Kamanga, R. Gilbert, and K. Wellard. 2002. Farmer and researcher partnerships in Malawi: developing soil fertility technologies for the near-term and far-term. *Experimental Agriculture* 38: 411–431.

Sovell, L.A., B. Vondracek, J.A. Frost, and K.G. Mumford. 2000. Impacts of rotational grazing and riparian buffers on physicochemical and biological characteristics of southeastern Minnesota, USA, streams. *Environmental Management* 26: 629–641.

Steenwerth, K.L., L.E. Jackson, F.J. Calderon, M.R. Stromberg, and K.M. Scow. 2002. Soil microbial community composition and land use history in cultivated and grassland ecosystems of coastal California. *Soil Biology and Biochemistry* 34: 1599–1611.

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. 1998. Agricultural chemical movement through a field-size watershed in Iowa: Subsurface hydrology and distribution of nitrate in groundwater. *Environmental Science and Technology* 32: 1039–1047.

Temple, S.R., D.B. Friedman, O. Somasco, H. Ferris, K. Scow, and K. Klonsky. 1994. An interdisciplinary, experiment station-based participatory comparison of alternative crop management systems for California's Sacramento Valley. *American Journal of Alternative Agriculture* 9: 64–71.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. *Soil Science Society of America Journal* 63: 961–971.

Workneh, F., and A.H.C. van Bruggen. 1994. Suppression of corky root of tomatoes in soils from organic farms associated with soil microbial activity and nitrogen status of soil and tomato tissue. *Phytopathology* 84: 688–694.

4

CHAPTER 4

Analyzing the Performance and Sustainability of Agricultural Systems

Indicators arise from values and they create values.
Not only do we measure what we value, we also come to value what we measure.
—Donella Meadows

Just as there are multiple ways to design systems experiments, there are several methods for analyzing the data from these experiments. This chapter presents typical quantitative and qualitative methodologies for analyzing systems and gives examples of their applications. Like the boundaries of a systems experiment, the statistical methods are determined by the questions being asked and by the experimental design.

Analyzing complex systems is challenging; try to include someone with statistical expertise, or work with a consulting statistician for the design and analysis phases.

This chapter covers three general approaches to agricultural systems analysis:

- Statistical and mathematical tools, including univariate and multivariate analyses and mathematical modeling
- Natural resource accounting methods, such as life cycle assessments and ecological footprints
- Sustainability indices/indicator frameworks.

TABLE 4.1. Cropping Systems Management at the USDA Agricultural Research Center Farming Systems Project

SYSTEM	CROP ROTATION (COVER CROPS IN BOLD)	YEARS IN ROTATION	TILLAGE	FERTILITY	WEED CONTROL
No-till (NT)	Corn-**rye**-soybean-wheat-soybean	3	None	Mineral fertilizers	Herbicide
Chisel Till (CT)	Corn-**rye**-soybean-wheat-soybean	3	Chisel, disk	Mineral fertilizers	Herbicide
Organic, 2-yr (Org2)	Corn-**rye**-soybean-**vetch**	2	Moldboard plow, chisel, disk, rotary hoe, cultivator	Legume and animal manure	Cultural
Organic, 3-yr (Org3)	Corn-**rye**-soybean-wheat-**vetch**	3	Moldboard plow, chisel, disk, rotary hoe, cultivator	Legume and animal manure	Cultural
Organic, 6-yr (Org6)	Corn-**rye**-soybean-wheat-alfalfa-alfalfa-alfalfa	6	Moldboard plow, chisel, disk, rotary hoe, cultivator	Legume and animal manure	Cultural

Each cropping system in the Farming Systems Project in Beltsville, MD has its own set of tillage, fertility, and weed-control practices and rotation length. See Figure 3.4 on p. 50 for more detail on the experimental design. Adapted from Cavigelli et al. (2008).

Statistical and Mathematical Tools

Systems experiments, by the nature of their design and goals, have multiple confounding factors that cannot be easily separated (Teasdale and Cavigelli, 2010). This means that a mixture of statistical approaches is often required.

Univariate and multivariate statistics are the most typical mathematical methods of systems analysis. Which approach to use will depend upon the type of experimental design, the type and quantity of data generated, and the hypotheses being tested. In some cases, univariate methods such as analysis of variance (ANOVA) or means separation are applied initially to analyze the performance of individual system components (e.g., crop yields, soil fertility parameters or water use). When certain factors show a trend, multivariate approaches can be applied to tease out relationships among these components.

In other cases, multivariate methods are used for the initial exploratory data analysis to identify which factors have the most influence on treatment differences. These methods create new variables that are linear combinations of the original variables. These new variables can be further analyzed using univariate statistics.

For organizational purposes, the next two sections are divided into univariate and multivariate approaches; in reality, these approaches are often used in tandem in large systems experiments.

Univariate Analysis

Univariate statistics are well suited for evaluating the effects of independent variables on dependent variables and have been used extensively in agricultural research. For example, in simulated, replicated agricultural systems where the field has been evaluated and blocked to account for in-field variability, or where the field is homogenous, univariate statistics are generally used to compare yield, weed biomass, soil nutrient availability, economic returns and other factors among treatments.

The Farming Systems Project (FSP) at the USDA Agricultural Research Center in Beltsville, Maryland, provides a good example of how univariate analysis can provide valuable information about system performance. The FSP is rare among systems experiments; it is one of the only long-term projects in the United States with three organic systems that differ in crop rotation length and complexity. Since the establishment of the FSP in 1996, researchers have used ANOVA and multiple linear regression to investigate the effects of three organic and two conventional mid-Atlantic cropping systems (Table 4.1) on crop yield, weed populations and dynamics, and nitrogen availability (Cavigelli et. al, 2008). Although the five cropping systems differ in many factors (e.g., tillage, nutrient source, herbicide use), univariate analysis still provides valuable insights into how these variables impact cropping system performance.

Basic ANOVA on data from the first 10 years (focusing on years with near-normal rainfall) showed that the three organic treatments produced consistently lower corn and soybean yields, larger weed populations, and lower soil N availability for corn than the two conventional systems.

The researchers then used covariance analysis to further tease out the effects of weed cover, nitrogen availability and corn populations on corn yield. This secondary analysis showed that nitrogen availability, weeds and corn populations accounted for 70–75, 21–25 and 4–5 percent, respectively, of the lower corn yields in the organic systems (Cavigelli et al., 2008). The analysis also suggested that the significantly higher corn grain yield in the six-year versus the two- and three-year organic rotations was associated with increased nitrogen availability and decreased weed competition under the longer, more complex crop rotation in the six-year system (Teasdale et al., 2004; Cavigelli et al., 2008; Teasdale and Cavigelli, 2010).

While this covariance analysis showed an association between various parameters and crop yield, it did not show causation. Thus, to measure the direct impact of weeds on yield, researchers set up subplots within the main plots. The "weed-free" subplots were hand weeded; weed populations in the adjacent "weedy" subplots reflected the standard management practices used in the main plot. Corn yield loss due to weeds was calculated using the following simple equation:

$$\text{Corn Yield Loss (percent)} = \frac{\text{(Corn yield in weed-free subplot)} - \text{(Corn yield in weedy subplot)}}{\text{(Corn yield in weed-free subplot)} \times 100}$$

Analysis of the subplots showed that corn yield loss due to weeds varied by year, ranging from 0.7 to 1 percent for every 1 percent increase in weed cover in dry years, and from 0.2 to 0.3 percent for every 1 percent increase in weed cover in normal or wet years (Teasdale and Cavigelli, 2010). These findings, resulting from the nuanced analysis of interactions between weather and weed impacts on corn yield, provide a good example of how subplots can be used to isolate one factor within an otherwise systems-level experiment, as discussed in chapter 3.

Multivariate Approaches to Data Analysis

Multivariate analysis, a broad category of methods used to simultaneously analyze relationships among many variables, can reveal dynamic changes within a system that univariate statistics cannot. In addition, multivariate analysis can provide interpretation of complex measurements obtained in real-world situations where it is difficult to control certain kinds of variation, such as at the landscape level and in existing agricultural systems. In addition to revealing phenomena that closely replicate natural systems, the multivariate approach controls for Type I errors.

Type I error: an experimental error that detects an effect that is not actually present.

The use of multivariate statistics is challenging. Results can be difficult to interpret because they are often expressed as new linear combinations of variables, and their significance may not be as obvious as when evaluating simple differences among means from univariate tests.

Multivariate analysis can seem unwieldy because very large sample sizes are needed. The number of observations required depends on the data, but a good rule of thumb is to have three to 20 observations for every response outcome generated; hence, a team investigating 50 response variables would need to collect between 250 and 1,000 observations (Arrindell and van der Ende, 1985; Velicer and Fava, 1998; MacCallum et al., 1999; Osborne and Costello, 2004). In general, fewer observations are needed for ecological and environmental data compared to the social sciences (Gauch, 1982).

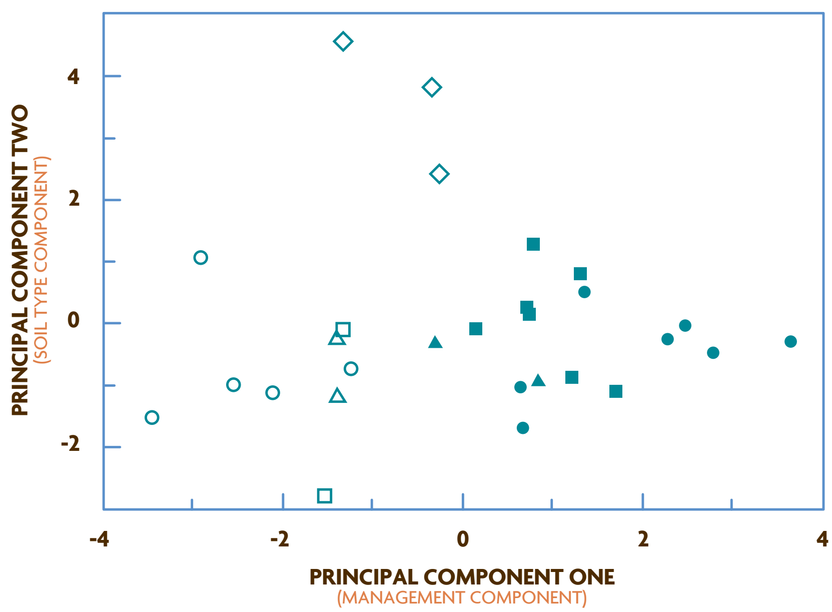
Advances in statistical methods and computing power have greatly improved the application of multivariate analyses to complex systems. These approaches are now routinely used to reveal interrelatedness among sets of variables of ecological and agricultural systems at the landscape level and in systems with multiple farm sites (Drinkwater et al., 1995; Wander and Bollero, 1999; Schipanski et al., 2010). The next section describes ways in which multivariate analyses have been used to compare agricultural system results across management regimes on working farms.

Commonly Used Multivariate Analyses

Some of the most commonly used multivariate approaches for systems analysis include principal components analysis (PCA, a dimension-reduction method), and classification techniques such as canonical discriminant analysis (CDA) and hierarchical clustering.

Drinkwater et al. (1995) used both PCA and CDA to evaluate system properties and relationships in a study that compared soil health, tomato yields, and disease and insect

FIGURE 4.1. Use of Principle Component Analysis (PCA) to Identify Sources of Soils Variability Between Organic and Conventional Fields



Using PCA, Drinkwater et al. (1995) found that soil type and management were the two largest sources of variability in soil characteristics between organic and conventional tomato fields. Open symbols represent conventional management; closed symbols represent organic management. Symbol shapes indicate soil order:
- ● = Entisols (recently formed soils lacking horizons);
- ■ = Alfisols (moderately weathered soils with clay deposits in the B horizon);
- ▲ = Mollisols (relatively high organic matter in the A horizons, well-structured);
- ◆ = Vertisols (high content of expanding lattice clay).

dynamics between organic and conventional farms. The goal of the study was to identify "ecological and agronomic characteristics of disparate agricultural management regimes." Twenty commercial farms, most of which grew fresh-market tomatoes, were categorized as organic or conventional based on their use of synthetic fertilizers, pesticides, organic soil amendments and biological pest control. One or more fields were sampled from each farm throughout two growing seasons. Within each field (29 fields in total), a 0.04 to 0.1-hectare sampling area was randomly selected and further divided into 20 sections, resulting in 20 subplots (1.5 square meters each) per field. Sampling time was determined by crop phenological stage, and samples were collected several times in each subplot throughout each growing season. Response variables measured included soil chemical and biological properties, root disease severity, biomass, fruit yield, insect pest damage, arthropod diversity, and soil microbial activity and diversity. At least 30 response variables were measured throughout each season from approximately 1,100 observations.

When multiple response variables are measured in subplots in independent systems, correlation (a lack of independence) will usually be present among the variables. This redundancy, or common information shared between measures, is referred to as shared variance, covariance or correlation. Correlation can cloud the larger picture, so the data must be reduced into smaller and new combinations of linear variables. Because response variables exist in multiple dimensions (e.g., X, Y, Z, P, Q), data reduction is also called dimension reduction; once reduced, the data can be analyzed in fewer dimensions, optimally one- or two-dimensional planes.

PCA is a widely used dimension-reduction technique that creates new variables called principal components (PCs), which are linear combinations of a set of correlated variables. The goal of PCA is to convert a data set with many intercorrelated variables into a smaller number of PCs to help reveal an underlying structure. PCA reduces the multidimensionality of variables into fewer dimensions that account for the variance of the system; each dimension, or axis on a graphical plot, represents one PC.

Drinkwater et al. (1995) used PCA on mean values (20 subplots per field) for 10 soil variables (percentage clay, cation exchange capacity, pH, wet aggregate stability, Kjeldahl nitrogen, electrical conductivity, potassium, phosphorus, inorganic nitrogen and nitrogen-mineralization potential) to identify major sources of variability. The analysis showed that management practices affected an array of biological and chemical properties and resulted in marked differences in soil quality between the organic and conventional fields. The PCA also identified management and inherent soil properties as the two major sources of variability (PC1 and PC2, respectively, Figure 4.1).

TABLE 4.2. Coefficients for the First Two Principal Components (PCs) for 10 Soil Variables

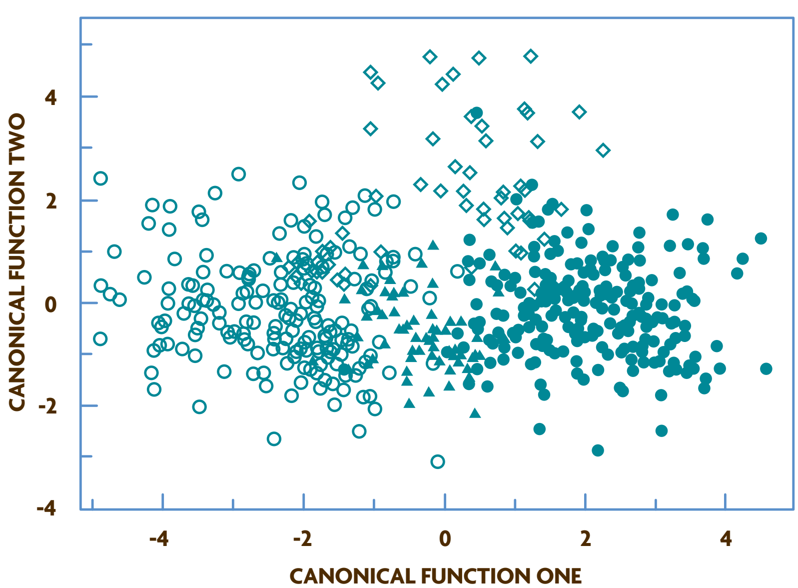
VARIABLE	PC1	PC2
Properties determined by parent soil type		
Percent clay	0.034	0.460*
Ephemeral properties mainly determined by management		
N-mineralization potential	0.482*	–0.082
Inorganic N ($NH_4^+ + NO_3^-$)	–0.482*	0.177
Electrical conductivity	–0.312*	0.169
Properties influenced by both management and soil type		
Cation exchange capacity	0.090	0.576*
pH	0.349*	–0.044
Exchangeable K	0.462*	0.046
Phosphorus	0.081	0.443*
Total Kjeldahl N	0.364*	0.244
Wet aggregate stability	–0.085	0.360*

Asterisks indicate variables that had sufficient loading to be considered significant. From Drinkwater et al. (1995).

The first two PCs (PC1 and PC2, shown in Figure 4.1) accounted for 31 and 24 percent of the total variance, respectively, based on the *loading*, which is a calculated coefficient by which each original variable is multiplied to identify an overall component score for each observation. For example, PC1 showed a clear separation of organic and conventional fields and was composed of soil properties likely to be strongly affected by management practices (inorganic nitrogen pools, nitrogen-mineralization potential and electrical conductivity, Table 4.2). Total Kjeldahl nitrogen, exchangeable potassium and pH also contributed significantly to separation along this axis, as indicated by the loadings, which suggested a strong effect of management on these properties (Table 4.2). In contrast, separation of three Vertisols under conventional management occurred along PC2, primarily due to greater clay content with high cation exchange capacity and wet aggregate stability. Organic and conventional fields did not segregate along this axis. Thus, PC2 reflected variation that was mostly associated with differences in soil type among sites.

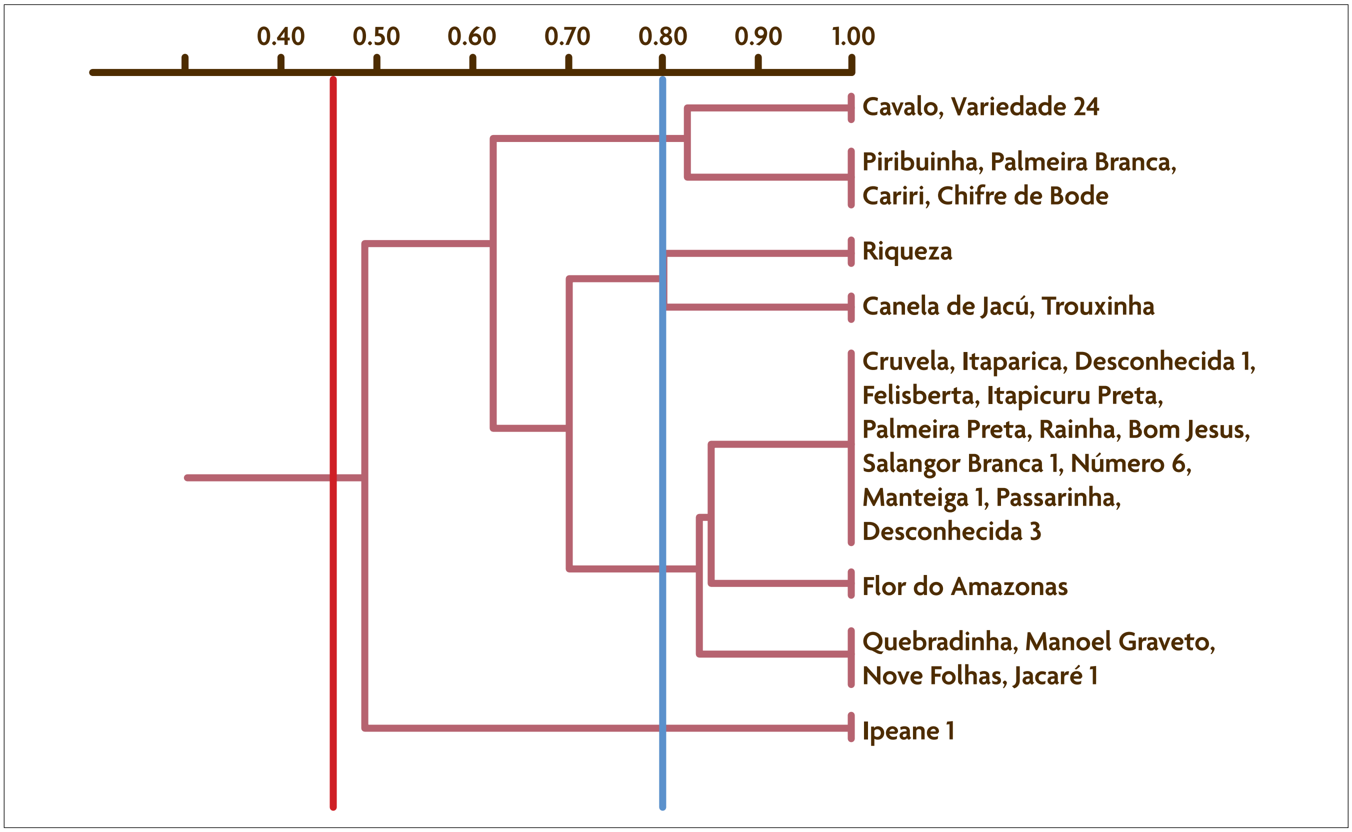
Based on PCA of the 10 soil variables, the authors identified four distinguishable management categories: fields in organic management for more than three years, fields in organic management for less than three years, conventional fields not on Vertisols, and conventional fields on Vertisols. They then used these categories in a CDA to test the hypothesis that management effects would be more pronounced un-

FIGURE 4.2. Canonical Discriminant Analysis (CDA) of Organic and Conventional Treatments to Segregate Effects of Management-Influenced and Inherent Soil Properties



The first and second canonical functions are shown, using only management-affected soil characteristics (total organic N, organic C, C:N ratio, N-mineralization potential, inorganic N, percent of inorganic N pool present as NH_4^+, pH and electrical conductivity). Symbols:
● = organic management >3 years;
▲= organic management <3 years;
○ = conventional management except sites on Vertisols;
◇ = conventional sites on Vertisols.
From Drinkwater et al. (1995).

FIGURE 4.3. Classification of Data by Hierarchies



A dendrogram indicating the genetic relationships among 28 cassava accessions obtained through hierarchical cluster analysis of isoenzyme systems in foliar tissues. The scale represents the proportion of genetic similarity. This dendrogram shows several varietal pairs with more than 80 percent similarity (pairs connected to the right of the blue line, e.g., Cavalo and Piribuinha) and reveals that the entire group has a similarity greater than 45 percent (the red line indicates 45 percent similarity). From Montarroyos et al. (2003).

der long-term (i.e., more than three years) management and to identify which soil variables were most closely associated with these management categories.

CDA is used to test and describe relationships among two or more group categories based on a set of variables (in this case, the 10 soil response variables). With CDA, variation among management categories is maximized while variation within categories is minimized, and the dimensionality of the data set is once again reduced into a smaller set of new variables, now called canonical functions. These newly derived canonical functions describe between-category variation; loadings within canonical functions describe the magnitude and direction of association of an original variable within a described category. Each canonical function (CAN) is a linear combination of independently measured variables and is independent of other canonical functions (Vaylay and van Santen, 2002). In the Drinkwater study, a significant Wilks' lambda value of 0.37 and a canonical correlation of $P = .0001$ between the four management categories and the first canonical function (CAN1) indicated that CAN1 explained the differentiation of the management groups (Figure 4.2). The analysis also showed that CAN1 was dominated by large loadings from pH, nitrogen-mineralization potential and Kjeldahl nitrogen and had a negative inorganic nitrogen loading (see Drinkwater et al., 1995 for detailed results of the CDA).

In other words, differences in management-influenced soil properties were greatest between fields that had been managed organically for more than three years and conventional sites not on Vertisols. Fields that were under organic management for three years or less were intermediate. As with PCA, CDA helped reveal which variables were most important for classification into different groups. In this case, total Kjeldahl nitrogen, organic carbon, inorganic nitrogen pools, pH, and electrical conductivity were significant factors in distinguishing between the three groups that remained after fields with confounding soil-type variation were removed. Using multivariate analyses, this study identified key differences in soil properties resulting from these distinct management regimes.

Hierarchical clustering analysis (HCA) is a classification method that produces a set of nested clusters organized as a hierarchical tree, or dendrogram (Figure 4.3). The dendrogram can be viewed on the observational level or as response measures, depending on the research scope (i.e., detailed or general). This flexibility is extremely helpful when examining relationships among entities or subgroups. HCA can reveal patterns that can lead to further hypothesis generation and testing, and it can assist in summarizing data as a precursor to regression, PCA or other classification methods.

Other Mathematical Analyses: Structural Equation Modeling and Path Analysis

Structural equation modeling (SEM) is an extension of the general linear model (GLM) and can be a more powerful alternative to multiple regression, path analysis, factor analysis, time-series analysis and analysis of covariance (Garson, 2010). An SEM model is essentially a composite hypothesis made up of a series of cause-and-effect relationships between variables using statistical dependencies (Shipley, 2000). SEM can account for additional complexities including nonlinearity, correlated independents, measurement error, correlated error terms and multiple latent variables. Latent variables are unobserved variables or factors that are measured by their respective indicators. For example, "quality of life" and "ecosystem resilience" represent complex characteristics that cannot be directly measured; these qualities are assessed using multiple traits as indicators.

In a soil nitrogen-mineralization study in a wheat field, de Ruiter et al. (1993) used SEM to analyze the contributions of different groups in the food web by simulating the deletion of ecologically significant groups of organisms from the soil ecosystem. They then measured the impact of the deletion of each group on nitrogen mineralization. The model showed that removing a group reduced overall nitrogen mineralization to a greater extent than would be expected based on the direct contribution of that group. Notably, amoebae and bacterivorous nematodes directly contributed to soil nitrogen mineralization at rates of 18 and 5 percent, respectively, but the deletion of amoebae or bacterivorous nematodes caused an overall reduction of nitrogen mineralization by 28 and 12 percent, respectively. These researchers used SEM to quantify the contributions of groups *within* the food web and to show that organisms function differently in simplified systems (here, incubations with a single group) than in a complex, intact system (in this case, a food web).

Path Analysis

Path analysis is a specific type of SEM that examines the strength of direct and indirect relationships among variables by disentangling causal processes (Lleras, 2005) and is the most commonly used SEM technique in the natural sciences. An extension of the regression model, path analysis

Time-Series Analysis

Time-series analysis is a multivariate approach that uses sequential data to determine the relationship between time and one or more variables. There are many approaches to using time-series analysis, ranging from regression analysis of a single time series (where multiple variables are measured through time), to using structured equation modeling to analyze more than one time series consisting of the same measurements.

Time-series analysis is an extremely valuable tool for analyzing long-term data sets and can be used to characterize temporal dynamics from a sequence of observations or to predict future values in the time series (Garson, 2010). Stronge et al. (1997) used time-series analysis of a 20-year data set to predict annual concentrations of NO_3^- in a lake surrounded by agricultural land. Their model determined the roles of climate variability and fertilizer use efficiency in driving nitrogen loss from drainage. The model showed that two climatic variables, rainfall from the previous summer and winter sun hours, were the most important drivers of NO_3^- leaching from agricultural landscapes. In a study focusing on management regime and biodiversity changes, Taylor and Morecroft (2009) analyzed 12 years of monitoring data to determine the effects of organic management on the diversity of plants and arthropods. Their time-series analysis of species abundance trends before and after conversion to organic management showed that biodiversity of some groups (e.g., moths and butterflies) increased following changes in management regime.

requires the usual assumptions of regression (e.g., uncorrelated errors) and the use of representative samples. Path models do not prove causation but they provide information on the relationships (e.g., directionality/magnitude and strength of effects) among underlying processes in a system (Lleras, 2005). Path analysis tests the fit of a correlation matrix between two or more causal models, using observational data, with as many regression equations as deemed necessary by the researcher. Competing path models are evaluated by estimating and by assessing the goodness-of-fit statistics, and the model that best fits the observed correlation matrix is selected (Garson, 2005). Path analysis can be highly sensitive to model specification, and spurious inclusion of unnecessary variables can strongly affect results.

Bellino et al. (2015) used path analysis to better understand the ecological interactions of three years of applications of varying amounts of compost. These researchers drew inferences about the relationships among compost amendments, soil organic matter, nutrient concentrations, microbial activity and soil contamination. Using 13 hypothetical models, they found that potassium and zinc, microbial respiration and total polycyclic aromatic hydrocarbon concentrations were strong indicators of soil nutrient availability, microbial activity and organic contamination.

Natural Resource Accounting

Natural resource accounting refers to any system that tracks stocks and flows of natural assets, including those derived from living organisms (e.g., wood, food, organic compounds), energy, and materials (e.g., raw minerals, nutrients, toxins, water). The three approaches discussed below: life-cycle assessment, ecological footprints and carbon footprints, all report outcomes in terms of stocks and flows of natural resources or emissions, but they differ in their units of analysis. Life cycle assessments analyze material and energy flows at all stages of a product's life and provide information on the cumulative environmental impacts of the product. An ecological footprint analyzes human consumption of biological resources and generation of wastes in terms of how much of an ecosystem is used, and then compares this to the biosphere's productive capacity in a given year. Carbon footprints are similar to ecological footprints but are more specific, measuring direct emissions of greenhouse gases.

Life Cycle Assessment

Life cycle assessment (LCA) was developed in the 1960s within the field of industrial ecology, as a "cradle-to-grave" approach for assessing the impacts of industrial systems and manufacturing processes on environmental and human health (Horne et al., 2009). An LCA begins with an inventory of the raw materials required to produce a product and ends at the point when all those materials are returned to the earth. All inputs and environmental releases to air, water and land are determined for each life cycle stage and/or major contributing process over the product's life span. In the early 1990s, researchers began using LCA to analyze food systems, specifically food processing and packaging. More recently, LCAs have been used to assess food crop, animal production, and biofuel feedstock systems.

Key characteristics of LCAs include:

"Cradle-to-grave" analysis.

A multidimensional approach. LCAs analyze pathways by which environmental damage occurs, based on environmental impacts. This approach assesses both immediate or local impacts (e.g., human toxicity, water use/contamination) and long-term or global concerns (e.g., global warming, depletion of nonrenewable resources).

Flexible functional units. The comparison and analysis of alternative systems is based on equivalency of service delivered. For example, instead of comparing the environmental impacts of one pound of herbicide A with one pound of herbicide B, the quantity compared would depend on the application rate over a given acreage. This normalizes the assessment with respect to the final service delivered. More than one functional unit can be used in the same analysis (e.g., CO_2 emissions per acre or per pound of yield).

Subjectivity. LCAs reflect subjective decision-making, particularly with respect to the design of the analysis (scope and functional unit) and the interpretation of outcomes (Horne et al., 2009). The interpretation of trade-offs across environmental impacts depends on the setting.

Strong comparative ability. LCAs provide a strong approach for comparing specific resource inputs (e.g., fertilizer, chemicals and energy) and multiple environmental consequences.

Application of Life Cycle Analyses to Agricultural Systems Research

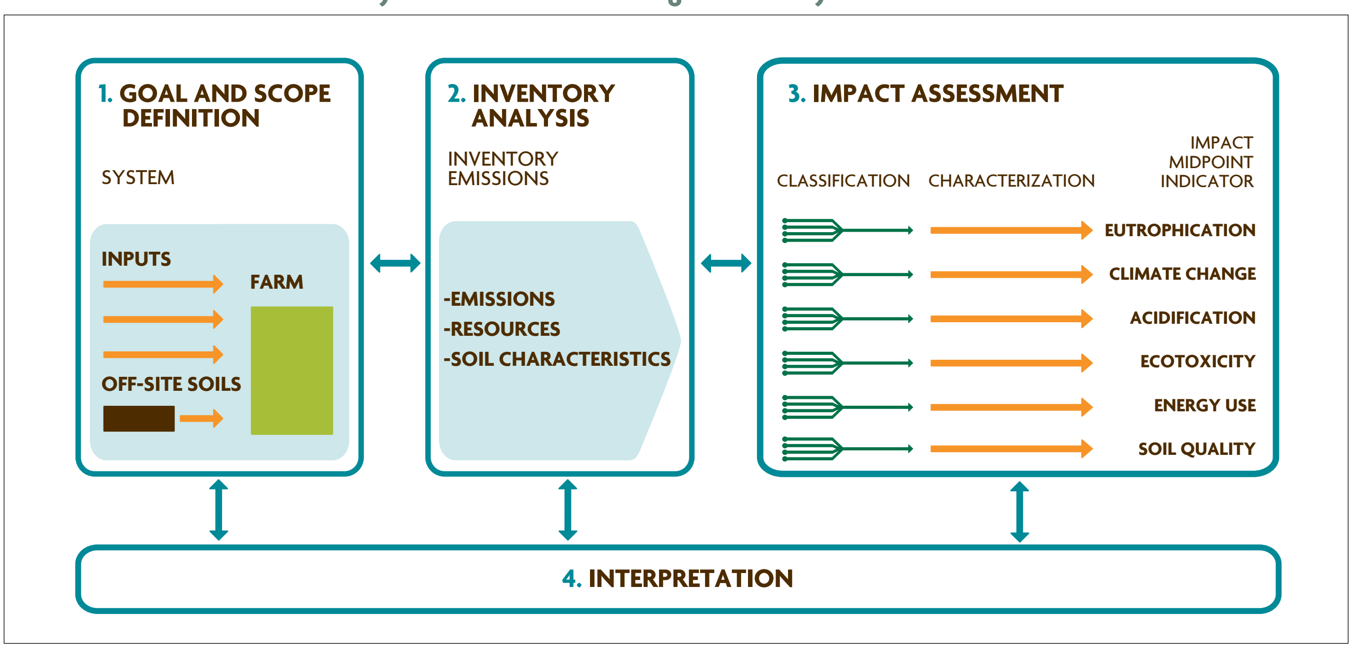
The use of LCA in agricultural systems is relatively new; in general, there are three ways to use LCA to evaluate agricultural systems:

Comparing life cycles for a product or service. This is the most common usage of LCA in agriculture. To compare life cycles, the scope and functional units must be consistent for all production systems. For example, organic and conventional production systems have been compared for a variety of products, including one ton of milk (Thomassen et al., 2008), one ton of bottled wine (Pizzigallo et al., 2008) and a one-kilogram loaf of wheat bread (Meisterling et al., 2009). Other studies have compared management strategies. For instance, Capper et al. (2008) evaluated the environmental impacts of rBST in dairy systems, Brentrup et al. (2004) assessed the environmental impact of varying fertilizer rates on wheat production (per ton of wheat), and Haas et al. (2001) compared milk production from intensive, extensive and organic grassland farming systems (per ton of milk).

Identifying parts of the life cycle where the greatest improvements can be made. This type of analysis entails a detailed assessment of a single product to evaluate the input requirements and environmental impacts of each stage of production through use and disposal. Landis et al. (2007) used LCA to evaluate the consequences of corn–soybean feed in terms of energy, carbon emissions, nitrogen and phosphorus flows, pesticides, and air pollutants. Through LCA, they identified the steps in grain production that account for the majority of air emissions (crop farming, fertilizers and on-farm nitrogen flows), and the steps that were less significant (seed production and irrigation). See the SARE case study (p. 76) of how one research team used LCA to monitor and develop an energy- and materials-independent dairy farm.

Comparing alternative products, processes or services. This type of analysis compares different products or processes that have the same function and is used in cases where there are distinct, interchangeable options. In other words, rather than simply comparing different production systems for specific products (e.g., orange production systems), the functional unit is broadened to compare the environmental outcomes of different products serving the same function (e.g., guavas, kiwis and oranges could be compared as a source of vitamin C). This type of analysis is very challenging and is relatively rare for agricultural systems compared to the first two applications. Examples include Eshel and Martin (2006) and Eshel et al. (2010), who examined the consequences of nutritionally sound animal-based diets versus plant-based diets consisting of similar caloric and protein contents.

FIGURE 4.4. Phases of the Life Cycle Assessment of an Agricultural System



Adapted from Garrigues et al. (2012).

Overview of LCA Methodology

LCA consists of four distinct processes (Figure 4.4):

- **Goal definition and scoping:** define and describe the product, process or activity.
- **Inventory analysis:** identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharges).
- **Impact assessment:** assess the potential human and ecological effects of energy, water and material usage, and assess the environmental releases identified in the inventory analysis.
- **Interpretation:** evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainties and assumptions used to generate the results.

(For more detailed information on how to apply LCA to agricultural systems, see EPA, 2006 and Horne et al., 2009).

FIGURE 4.5. Life Cycle Assessment (LCA) System Boundaries

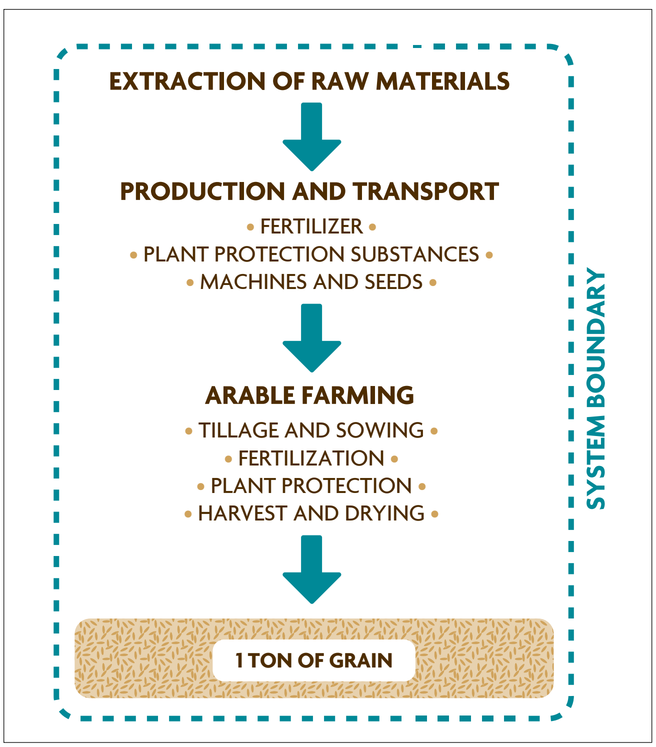


Illustration of a wheat system analyzed with LCA, showing how the life cycle and system boundary reflect the functional unit. From Brentrup et al. (2004).

LCA stage one: goal definition and scoping. Goal definition and scoping determines the purpose and expected outcome of the study, establishes the system boundaries, and defines the functional units (FU) and assumptions. System boundaries can be illustrated by a general input and output flow diagram (Figure 4.5). All operations that are part of the life cycle of the product, process or activity fall within the system boundaries. The purpose of the FU is to provide a reference unit to which the inventory data are normalized (e.g., application rates for agrochemicals are usually normalized per acre or other land-area unit). The FU varies across studies and is determined by the system boundaries, the product or processes of interest, the type of environmental impact and the aims of the investigation.

The system boundary can be defined in several ways in LCA studies comparing agricultural production systems. Brentrup et al. (2004) used LCA to determine the environmental impacts of different fertilizer management regimes in wheat production systems. They defined the functional unit as one ton of wheat; their system boundaries began with the extraction of raw materials and ended with the harvest and drying of the wheat (Figure 4.5; Brentrup et al., 2004). In contrast, Meisterling et al. (2009) compared organic and conventional wheat production using 0.67 kilograms of wheat flour as their functional unit; bread was their target product and this FU represented the amount of flour used to make a one-kilogram loaf. This latter study encompassed a larger system that included all of the steps in wheat production, harvest, transport and processing into flour. Brentrup et al. (2004), however, limited their analysis to crop production because their functional unit was unprocessed wheat grain. Other common functional units used in agricultural LCAs include the nutritional value or quality of the product and the land area required per unit of production.

Decisions about the LCA scope and functional units can determine the conclusions drawn about how management systems affect the environment. For example, in an LCA comparing three pig production systems (Basset-Mens and van der Werf, 2005), environmental impacts were expressed using two different functional units: per kilogram of live pig weight produced and per hectare of land used (including off-farm land used to produce crop-based ingredients for feed). When the systems were compared in terms of impacts per land area used, the organic and red-label systems had better performance; the relative performance of the systems was significantly different when impacts per kilogram of pig production was used as the functional unit.

LCA stage two: life cycle inventory analysis. The life cycle inventory analysis quantifies energy and raw material requirements, atmospheric and waterborne emissions, solid wastes, and other releases for the entire life cycle of a product or farming system. It is the most resource-intensive and time-consuming stage because it requires large amounts of data collection. LCA software is available for purchase and includes databases on the transport, processing and production of commonly used products such as plastic, refined metals and cardboard. Several free LCA software programs are also available (EPA, 2006); these programs contain data for processes that are not product-specific, such as general data on the production of electricity, agricultural inputs and fuel. The USDA is working to improve the accessibility, transparency and quality of the data. (See the LCA Digital Commons project led by the National Agriculture Library, www.lcacommons.gov.)

When using LCA in agricultural systems analysis, practices such as tillage frequency or application rates of pesticides or soil amendments require site-specific data. For a complete LCA, all inputs and outputs from the processes and materials used in crop production must be included. Inputs include energy (renewable and nonrenewable), water, and raw materials. Outputs include products and coproducts, emissions (e.g., the greenhouse gases CO_2, CH_4, SO_2, N_2O, NO_x and CO), chemicals (e.g., nutrients, chlorinated organic compounds and other agrochemicals), biotic losses (e.g., genes or exotic organisms) to air, water and soil, solid wastes, and soil loss or degradation.

LCA stage three: impact assessment. Impact assessment evaluates the impacts of resource use and emissions identified during the inventory analysis; its purpose is to address ecological and human health effects and consequences of resource depletion. For example, an evaluation of irrigation systems might show that furrow irrigation uses more water but that disposable drip tape uses more material inputs and produces more waste. In this example, the assessment would weigh water-use efficiency against the use of fossil fuels (in the manufacture of plastic) and the generation of solid waste to determine which system had the more severe environmental impact. A complete accounting of inputs and outputs improves the capacity to compare production systems, even when the resources used and emissions generated vary across the systems or processes under study.

LCA Stage four: interpretation. Although the LCA framework is based on detailed guidelines and extensive databases, this approach relies heavily on interpretation by the research team throughout all stages (Figure 4.4). Conclusions drawn and recommendations made reflect the regional, cultural and institutional values of the individuals conducting the LCA. As a result, although the rigor and consistency of LCA analysis have improved greatly, it is still subject to interpretation. For example, in the furrow versus drip irrigation scenario described above, the importance assigned to each environmental impact is site specific and based on subjective judgment. In a region with serious water limitations, for instance, reduced demand for irrigation water could be the environmental priority, so the team might decide that the advantages of the drip system outweigh its drawbacks (e.g., increased solid waste and greater greenhouse gas emissions from the manufacture of drip materials).

Given this "situational" aspect of LCA, be very clear about the rationale and goals of an LCA, and be prepared to explain the basis for conclusions drawn. Include all data collected in the inventory stage and the impact assessment. Transparency in the methods used to collect and calculate data and in the basis for interpretation of the LCA is critical; this transparency greatly increases the potential to compare and synthesize results from different LCAs of the same product or similar production system. For example, in the case of wheat production on p. 70, the decision by two teams to use different functional units (i.e., raw wheat grain versus flour) resulted in different system boundaries, which could impact the interpretation of these two LCAs.

Strengths and Limitations of LCA

A key strength of the LCA approach is that it enables the use of a single analysis to consider multiple resources and impacts and to compare environmental consequences from local to global scales. As a result, LCA can be useful in a variety of agricultural systems research settings, from field station projects comparing multiple cropping systems, to on-farm projects conducted at the farm scale, to projects comparing agricultural systems at regional or national levels. Furthermore, LCA has a long history of application in industry and manufacturing, which has resulted in a vast amount of information relevant to agricultural systems.

The flexibility that makes LCA a compelling tool for guiding management decisions toward greater sustainability presents challenges for drawing broad, generalizable conclusions. The LCA design can affect the outcomes and conclusions, so consider all design details of each LCA before comparing results (van der Werf et al., 2007; Horne et al., 2009). Also, while detailed output from LCAs is valuable, interpreting the results can be challenging, and subjective judgments are inevitable (Horne et al., 2009). Full LCA analyses can be too complex for extension and education purposes (although some LCA output, such as energy use and carbon footprint findings, can be more accessible).

Computation of emissions is the least reliable aspect of LCAs of agricultural ecosystems, because emissions are generally from nonpoint sources and there are insufficient empirical data. Some useable data have been collected through projects such as the National Agriculture Library's LCA Digital Commons and the National Renewable Energy Laboratory's Life Cycle Inventory database, but significant gaps remain, especially due to the nonpoint characteristic of agricultural systems.

Lastly, LCA focuses mostly on ecological and environmental systems, although more recently LCA has been applied in a social context as well (Norris, 2015).

Ecological Footprints

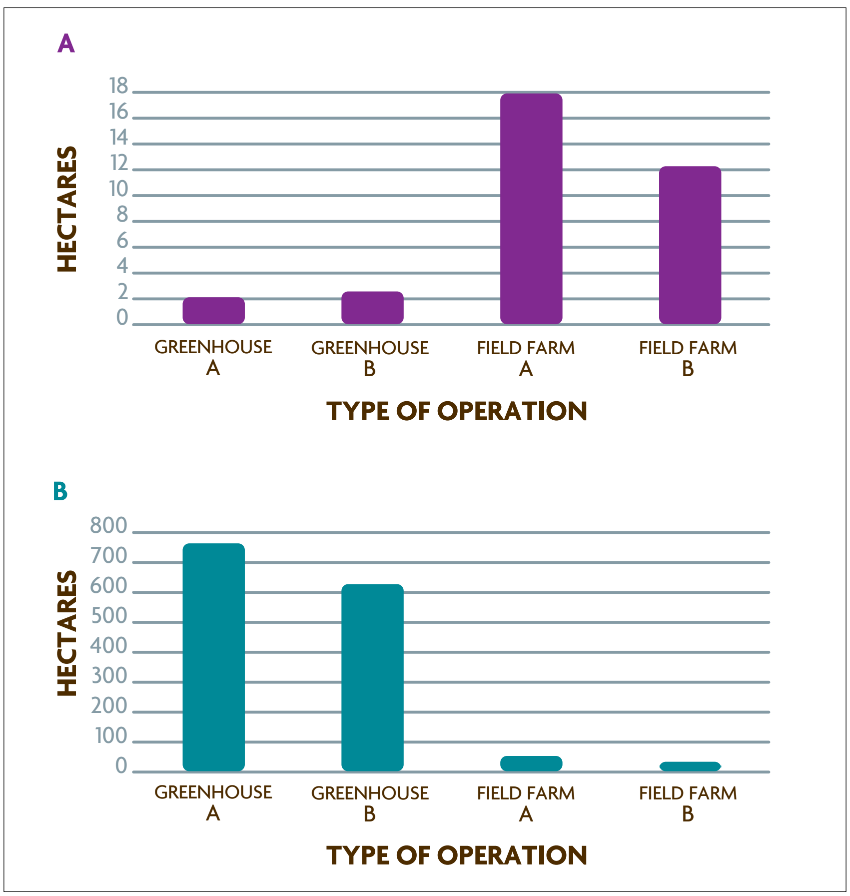
Ecological footprint accounting was developed in the early 1990s (Wackernagel and Rees, 1995; Kitzes and Wackernagel, 2009) and is used to analyze human consumption of biological resources and generation of wastes in a specified ecosystem area, which is then compared to the biosphere's productive capacity in a given year. The ecological footprint approach attempts to answer a single question: "How much of the planet's capacity is used relative to what is available?"

> **Ecological overshoot: when population demand exceeds the supply or biocapacity of the environment.**

The ecological footprint approach is not a predictive tool. Rather, it provides information that can be used to track changes through time and to assess past and current resource consumption. This approach has been applied to a wide assortment of scales and units of analysis (Ewing et al., 2008); perhaps the most well-known application is its use in estimating the extent of global ecological overshoot (Wackernagel et al., 1999). Ecological footprints can be calculated for individuals, groups (e.g., the population of a city, watershed or nation), and activities (e.g., agricultural production) and can be used in studies at larger scales (e.g., the watershed or foodshed).

Ecological footprints are calculated by converting the inputs required for a product or process to a corresponding area of land or water that is needed to produce the resources or assimilate the emissions associated with that product or process. The calculations usually include six land-use categories: cropland, pasture, forest, energy land, built-up land and fishing ground. These areas are converted to their global hectare equivalents using yield and equivalence factors (Monfreda et al., 2004). The equivalence factor reflects differences in productivity among land-use categories; the yield factor captures the difference between local and global average productivity of the same bioproductive land type (Monfreda et al., 2004). Each resulting global hectare is a standardized and productivity-weighted unit of global average productivity (Monfreda et al.,

FIGURE 4.6. Ecological Footprint of Field Versus Greenhouse Tomatoes



(A) Area required to grow 1,000 tons of tomatoes per year. (B) Calculated ecological footprint (area "appropriated" to grow 1,000 tons of tomatoes per year). From Wada (1993).

2004). Footprints are compared to the biocapacity of a given area; biocapacity represents the maximum available resource capacity, measured in area of bioproductive land, and varies depending on the goal of the analysis. Biocapacity is considered a threshold and is used as a benchmark for the footprint analysis (Wackernagel and Rees, 1995; Monfreda et al., 2004).

Application to Agricultural Systems Research

Ecological footprint accounting is in the early stages of application to agricultural systems. So far, it has been most commonly used to compare different production systems for a particular crop, such as tomatoes (Wada, 1993) or wine (Niccolucci et al., 2008). Wada (1993) compared the land area and energy/material inputs required to grow a thousand tons of tomatoes in hydroponic greenhouses to the corresponding requirements for high-input, field-based production. He found that per unit growing area, the greenhouses were six to nine times more productive than the field (Figure 4.6). However, when all energy and material flows were taken into account, the ecological footprint of greenhouse tomato production was 14 to 20 times larger than that of high-input field production (Figure 4.6), revealing the intensive resource requirements of heated hydroponic greenhouses.

Although conventional metrics show conventional agricultural systems to be more productive on a simple yield-per-acre basis, footprint analysis reveals the opposite: these systems subsidize production through the use of nonrenewable resources such as fossil fuels. Footprint analysis often shows that greater yields per acre achieved through increased use of technology and industrial inputs actually increase the *appropriated* land requirements per unit of production, when all the inputs are considered. While LCA can provide similar conclusions, ecological footprint accounting integrates resource use by converting everything to land area equivalents. This can be a useful tool for communicating differences in resource use to farmers and other stakeholders who are more familiar with yield-per-acre comparisons.

Strengths and Limitations

Ecological footprint accounting has much in common with LCA. It is a data-intensive approach with a strong ecological basis for assessing the performance of an entire system. Data sets and calculation methods for ecological footprint assessments have improved greatly since the 1990s (Ewing et al., 2008) and are continuing to improve (Kitzes et al., 2009), and extensive databases and other resources are available to support these analyses.

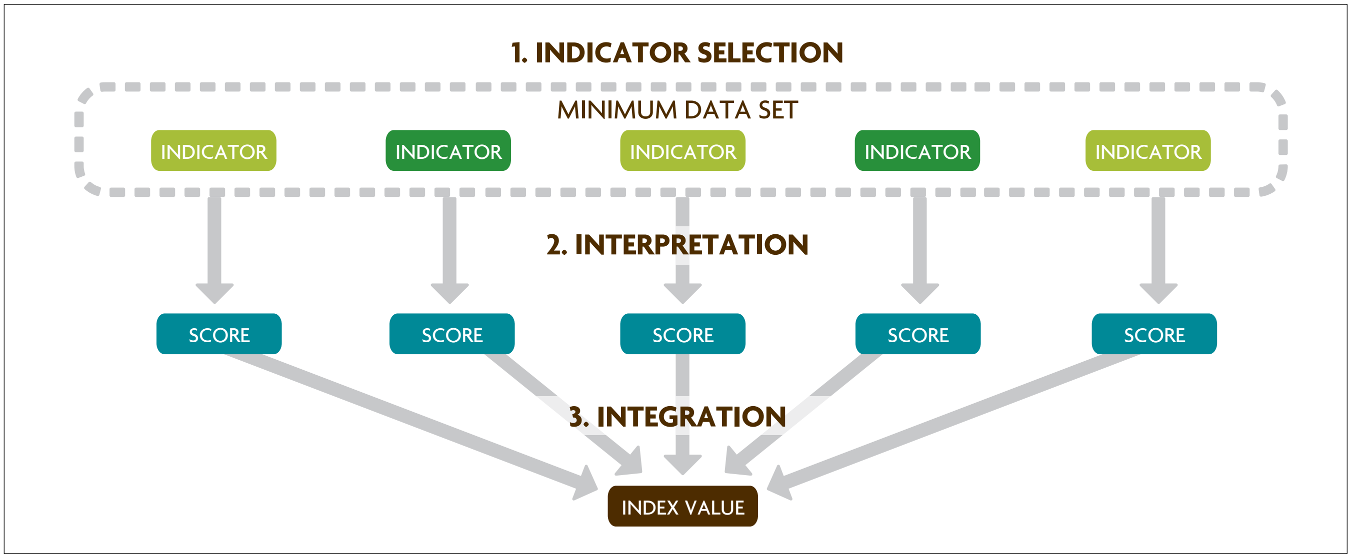
The most notable limitations of ecological footprint accounting are in the analysis of greenhouse gas emissions and water use. Using current methodology, greenhouse gases can only be accounted for as land area required to sequester CO_2, so all greenhouse gases must be converted to CO_2 equivalents. Also, although water is a limited resource, it is not derived from ecosystem production and is not accounted for in the land-area conversions. Researchers are working to resolve these key problems and other limitations (Kitzes et al., 2009; Wackernagel, 2009). Footprint analyses cannot account for some aspects of environmental sustainability, such as resource depletion outside the biosphere (for example, the mining of metals) and the environmental impact of toxins and materials that do not decompose. These impacts cannot easily be converted to use of a portion of the biosphere. In systems where resource depletion and toxic outputs are important, LCA can complement footprint accounting.

Despite its limitations, ecological footprint accounting is a valuable tool for evaluating systems at a variety of scales—farm, regional, national and global—and it allows per-capita comparisons. Furthermore, footprints eliminate the subjective judgment required at many stages of LCA by converting resource use and consequences to a single quantitative unit. Footprint analyses share a common basis and set of calculations; as a result, all ecological footprint assessments can cite the same methodology, and broad comparisons can be made without checking the underlying assumptions and calculations. This ability to compare widely divergent systems using the same framework on the same terms is a strength of footprint analysis that complements the application-specific nature of LCA.

Carbon Footprints

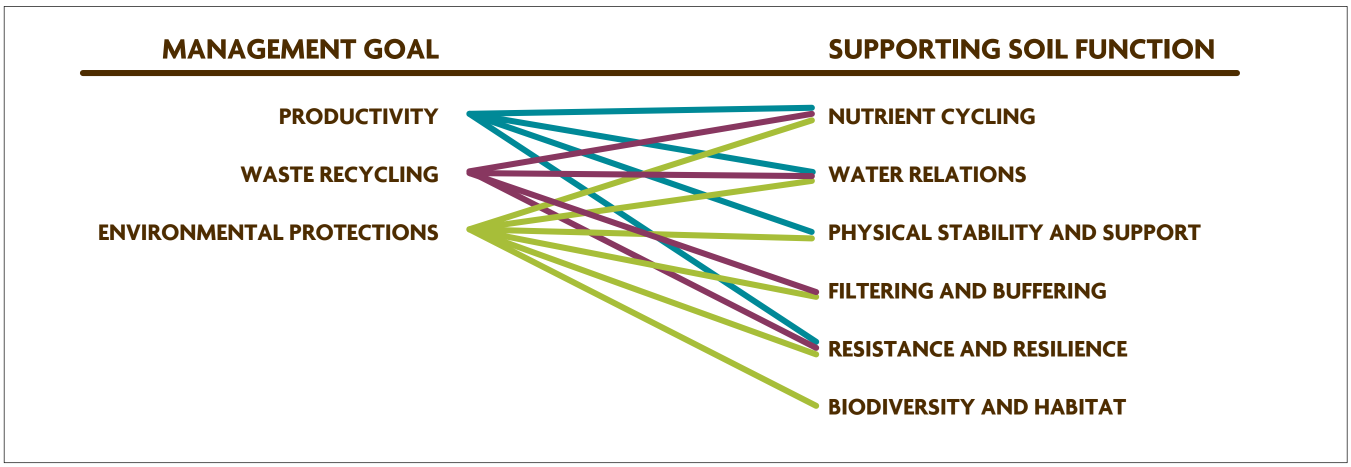
Previously, efforts to study greenhouse gas reductions in agricultural systems centered only on the sequestration of carbon as soil organic matter (Lal et al., 2007). Since agricultural production generates significant greenhouse gas emissions, however, a full accounting of both carbon emissions and sequestration is needed. The net balance between emissions and absorption is the “carbon footprint” and includes production of all greenhouse gases, including N_2O and CH_4, which are converted to CO_2 equivalents. Carbon footprints have been used to compare different types of crops and agricultural production systems, such as organic versus conventional (Hillier et al., 2009) and historical versus contemporary dairy production (Capper et al., 2008). They have also been used to compare the greenhouse gas consequences of different human diets (Stehfest et al., 2009).

FIGURE 4.7. Indicator Index



Integration of indicators into an index. From Andrews et al. (2004).

FIGURE 4.8. Potential Management Goals and Associated Soil Functions Used to Select Appropriate Soil Quality Indicators



From Andrews et al. (2004).

Using Indicators to Assess Agricultural Systems

An indicator is an observed or measured variable that reflects the state of a system (Mayer, 2008). In agricultural systems, crop health is monitored using indicators such as plant architecture and leaf color and shape. Farmers use quantitative soil tests, soil color and surface texture, amount of runoff, and the “feel” of tillage (e.g., how hard the tractor has to work during plowing) to evaluate the status of their soils. The presence or absence of certain weedy species can also be used as an indicator of soil nutrient status.

Sustainability Indicators and Indices: Practical Considerations

An “indicator framework” is an organizational strategy for grouping many indicators together to assess the state of a complex system. For example, income, access to social services and land tenure could be used to determine farm-family quality of life, and soil fertility, climate, and yield stability could be used to measure farm productivity.

Because a single indicator cannot fully represent a multidimensional entity such as an agricultural system (Meadows, 1998; Mayer, 2008), system assessment frameworks often rely on multiple indicators. Indicators can be aggregated into an "index" using algorithms (Mayer, 2008) and techniques such as averaging, ratios and principal components analysis (Mayer, 2008). Figure 4.7 shows a conceptual diagram of indicators being scored and combined into an index that provides quantifiable information about a system, in this case, soil health. (Andrews et al., 2004).

Andrews et al. (2004) used this method to "operationalize" soil health (i.e., to specify qualities that can be quantified by measurable indicators). They defined three soil management goals—productivity, waste recycling and environmental protection—and linked these goals to six soil functions that could be quantified by measurable indicators (Figure 4.8). For example, functions such as "physical stability and support" can be quantified by measuring bulk density, water-stable aggregates, porosity, and/or soil strength. This indicator framework enabled the vague concept of soil health to be operationalized and compared across different management regimes (Andrews et al., 2004). Such frameworks or indices are key to comparing and evaluating complex, multidimensional systems.

To operationalize the broader concept of sustainability, comprehensive frameworks and indices are used to evaluate the ecological and social sustainability of agricultural systems. Many excellent books (Jørgensen et al., 2009) and reviews (Mayer et al., 2004; Mayer, 2008; Speelman et al., 2007) detail these efforts.

SARE CASE STUDY Using Life Cycle Assessment at the University of New Hampshire's Organic Dairy Research Farm

University of New Hampshire compost facility. Photo courtesy of John Aber

When the University of New Hampshire (UNH) converted a decades-old, 300-acre farm into an organic dairy in 2005, making it the country's first commercial-scale organic dairy at a land-grant university, researchers wanted to identify management actions that could make the farm self-sustaining in its nutrient and energy requirements. To do this, the research team has been using a life cycle assessment (LCA) approach to better understand a range of complex physical, biological and human factors affecting farm activities.

The stated objective of the nine-year SARE-funded study, which began in 2008, is to measure all of the materials and energy flows occurring across the farm in an annual production cycle, to eventually achieve a closed-system, energy-independent operation. This means, for example, that the farm will potentially satisfy most of its nutrient needs through careful manure management and composting, without losing nutrients into the nearby Lamprey River, and that a 160-acre forest on the property will provide both animal bedding and energy.

"There was nothing out there that had looked at the energy or nutrient balance of organic dairies, so it seemed like a wonderful place to start," says John Aber, a UNH forest ecologist who is coordinating the project. "We can actually look at whole-farm operations in the context of economic and environmental sustainability."

As a first step, researchers created a nutrient flow diagram and an energy inventory assessment, using the farm as the boundary. They also studied poorly understood aspects of nutrient flows and energy requirements, such as how nutrients exit the farm's pastures into waterways, and the potential of the on-farm woodlot to provide energy for heating.

A common, effective way in which LCA is applied to agricultural research is by using collected data to identify parts of a cycle that are ripe for improvements. In this case, UNH faculty have been conducting mini-studies of parts of the cycle related to manure handling and composting, on-farm bedding production and the use of geothermal energy for milk cooling, and to compare mixed crop and forage systems. Their grant is structured so that promising techniques they identify will be implemented and continually refined.

A major challenge in using the LCA approach in an agricultural context relates to capturing accurate data on all the possible components and stages of the cycle being studied. Aber and his colleagues defined their goals and established their system boundaries at the farm level in part to help them manage this complexity. For example, by having the goal of making the farm energy independent—instead of making the life cycle of the milk produced there energy independent—they do not need to account for some factors for which data collection might pose a challenge, such as transportation of goods to and from the farm.

Another advantage to setting the system boundary at the farm level was that many records and data sets already existed. For example, the initial analysis of nitrogen flows into and out of the farm relied heavily on existing university records. To prepare the nitrogen budget, researchers first used these records and on-farm measurements to quantify major imports onto the farm such as hay, grain and atmospheric deposition; internal nutrient sources such as manure, hay and forage; and the primary output, milk. Next, they used a literature review to attach numbers to the budget items. By doing this, the researchers identified the major knowledge gaps that required more study, including on-farm manure production, nutrient exports into the environment and the potential productivity of the farm's woodlands for bedding and energy, all of which became the focus of more in-depth studies.

Coinvestigators Bill McDowell, an ecosystem ecologist, and Matt Davis, a hydrogeologist, helped fill the gap in understanding how nutrients are exported from the farm into the environment. They conducted a two-year study to establish a three-dimensional groundwater model of the farm to see how and where water and nutrients were escaping. In addition, they sampled groundwater wells and surface runoff monthly to quantify nutrient exports and establish important baselines.

These baselines will allow researchers to assess changes they make to management practices, such as improvements to the physical configuration of barns, to the way manure is handled and to grazing strategies. McDowell says, "We can't tell how successful we're being in terms of environmental impacts and retaining valuable nutrients unless we're monitoring what is lost in runoff."

Researchers are also studying alternative production techniques that will move them closer to their goal of achieving a closed-system, energy-independent farm. For example, Davis is planning to install and test a geothermal system for chilling the milk before it goes into storage tanks, to reduce

Mechanical room with view of heat exchange unit. Photo courtesy of John Aber

dependence on off-farm energy. Cool water will be pumped from about 300 feet underground and will be run in pipes beside separate pipes containing milk, thereby cooling the milk. Then, the water will be recycled underground to cool before being pumped back up, starting the process anew. Over about two years, Davis will quantify how much energy is transferred from the milk to the geothermal well and will monitor temperature to see whether the well's temperature rises over time, which would determine the system's long-term sustainability and efficacy.

"It's not well quantified that these milk chillers really help reduce the energy load on the system," Davis says. "This is going to be useful even beyond dairy, to understand how this energy is flowing into this geologic material."

The researchers using the Organic Dairy Research Farm also see potential for other systems-based studies. For example, faculty members plan to incorporate multiple species into grazing systems, develop on-farm processing for cheese and other value-added products, conduct a carbon footprint analysis, and study the farm in the broader context of regional food systems.

References

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Science Society of America Journal* 68: 1945–1962.

Arrindell, W.A., and J. van der Ende. 1985. An empirical test of the utility of the observations-to-variables ratio in factor and components analysis. *Applied Psychological Measurement* 9: 165–178.

Basset-Mens, C., and H.M.G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. *Agriculture, Ecosystems, and Environment* 105(1–2): 127–144.

Bellino, A., D. Baldantoni, F. De Nicola, P. Iovieno, M. Zaccardelli, and A. Alfani. 2015. Compost amendments in agricultural ecosystems: confirmatory path analysis to clarify the effects on soil chemical and biological properties. *The Journal of Agricultural Science* 153(2): 282–295.

Brentrup, F., J. Küsters, J. Lammel, P. Barraclough, and H. Kuhlmann. 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. *European Journal of Agronomy* 20(3): 265–279.

Capper, J.L., E. Castañeda-Gutiérrez, R.A. Cady, and D.E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. *Proceedings of the National Academy of Sciences of the United States of America* 105(28): 9668–9673.

Cavigelli, M.A, J.R. Teasdale, and A.E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the Mid-Atlantic region. *Agronomy Journal* 100(3): 785–794.

de Ruiter, P.C., J.C. Moore, K.B. Zwart, L.A. Bouwman, J. Hassink, J. Bloem, J.A. Devos, J.C. Marinissen, W.A.M. Didden, G. Lebbink, and L. Brussaard. 1993. Simulation of nitrogen mineralization in the belowground food webs of two winter-wheat fields. *Journal of Applied Ecology* 30: 95–106.

Drinkwater, L.E., D.K. Letourneau, F. Workneh, A.H.C. van Bruggen, and C. Shennan. 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. *Ecological Applications* 5(4): 1098–1112

EPA. 2006. *Life Cycle Assessment: Principles and Practice*. EPA/600/R-06/060, 80 pages. http://nepis.epa.gov.

Eshel, G., and P.A. Martin. 2006. Diet, energy, and global warming. *Earth Interact*: 10: 1–17.

Eshel, G., P.A. Martin, and E.E. Bowen. 2010. Land use and reactive nitrogen discharge: effects of dietary choices. *Earth Interact* 14: 1–15.

Ewing, B., S. Goldfinger, M. Wackernagel, M. Stechbart, S. M. Rizk, A. Reed, and J. Kitzes. 2008. *The Ecological Footprint Atlas 2008*. Global Footprint Network: Oakland, CA.

Garrigues, E., M.S. Corson, D.A. Angers, H.M.G. van der Werf, and C. Walter. 2012. Soil quality in Life Cycle Assessment: towards development of an indicator. *Ecological Indicators* 18: 434–442.

Garson, G.D. 2010. *Creating simulated datasets*. G. David Garson and Statistical Associates Publishing: Asheboro, NC.

Garson, G.D. 2005. *PA 765 Statnotes: An Online Textbook*. North Carolina State University:http://faculty.chass.ncsu.edu/garson/PA765/statnote.htm.

Gauch, H.G. 1982. *Multivariate Analysis in Community Ecology*. Cambridge University Press: Cambridge, UK.

Haas, G., F. Wetterich, and U. Köpke. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems and Environment* 83(1–2): 43–53.

Horne, R., T. Grant, and K. Verghese. 2009. *Life Cycle Assessment: Principles, Practice and Prospects*. CSIRO Publishing: Collingwood, Australia.

Hillier, J., C. Hawes, G. Squire, and A. Hilton. 2009. The carbon footprints of food crop production. *Journal of Agricultural Sustainability* 7(2): 107–118.

Jørgensen, S., L. Xu, and R. Costanza, eds. 2009. *Handbook of Ecological Indicators for Assessment of Ecosystem Health. 2nd Edition. Applied Ecology and Environmental Management Series*. Taylor & Francis, CRC Press: Boca Raton, FL.

Kitzes, J., A. Galli, M. Bagliani, J. Barrett, G. Dige, S. Ede, K. Erb, S. Giljum, H. Haberl, C. Hails, L. Jolia-Ferrier, S. Jungwirth, M. Lenzen, K. Lewis, J. Loh, N. Marchettini, H. Messinger, K. Milne, R. Moles, C. Monfreda, D. Moran, K. Nakano, A. Phyälä, W. Rees, C. Simmons, M. Wackernagel, Y. Wada, C. Walsh, and T. Wiedmann. 2009. A research agenda for improving national Ecological Footprint accounts. *Ecological Economics* 68: 1991–2007.

Kitzes, J, and M. Wackernagel. 2009. Answers to common questions in Ecological Footprint accounting. *Ecological Indicators* 9: 812–817.

Lal, R., F. Follett, B.A. Stewart, and J.M. Kimble. 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science* 172: 943–956.

Landis, A.E., S.A. Miller, and T.L. Theis. 2007. Life cycle of the corn-soybean agroecosystem for biobased production. *Environmental Science and Technology* 41(4): 1457–1464.

Lleras, C. 2005. Path analysis. *Encyclopedia of Social Measurement* 3: 25–30.

MacCallum, R.C., K.F. Widaman, K.J. Preacher, and S. Hong. 1999. Sample size in factor analysis: the role of model error. *Multivariate Behavioral Research* 36(4): 611–637.

Mayer, A.L. 2008. Ecologically-based approaches to evaluate the sustainability of industrial systems. *International Journal of Sustainable Society* 1(2): 117–133.

Mayer, A.L., H.W. Thurston, and C.W. Pawlowski. 2004. The multidisciplinary influence of common sustainability indices. *Frontiers in Ecology and the Environment* 2: 419–426.

Meadows, D.H. 1998. *Indicators and Information Systems for Sustainable Development: A Report to the Balaton Group*. Sustainability Institute: Hartland Four Corners, VT.

Meisterling, K., C. Samaras, and V. Schweizer. 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production* 17(2): 222–230.

Monfreda, C., M. Wackernagel, and D. Deumling. 2004. Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments. *Land Use Policy* 21(3): 231–246.

Montarroyos, A.V.V., M.A.G. de Lima, E.O. dos Santos, and J.G.E. de Franca. 2003. Isozyme analysis of an active cassava germplasm bank collection. *Euphytica* 130: 101–106.

Niccolucci, V., A. Galli, J, Kitzes, R.M. Pulselli, S. Borsa, and N. Marchettini. 2008. Ecological Footprint analysis applied to the production of two Italian wines. *Agriculture, Ecosystems, and Environment* 128(3): 162–166.

Norris, C.B., and J. Reveret. 2015. Partial Organization and Social LCA Development: The Creation and Expansion of an Epistemic Community. In *Social Life Cycle Assessment*, ed. S.S. Muthu. Springer: Singapore.

Osborne, J.W., and A.B. Costello. 2004. Sample size and subject to item ratio in principal components analysis. *Practical Assessment, Research, and Evaluation* 9(11).

Pizzigallo, A.C.I., C. Granai, and S. Borsa. 2008. The joint use of LCA and energy evaluation for the analysis of two Italian wine farms. *Journal of Environmental Management* 86(2): 396–406.

Schipanski, M.E., L.E. Drinkwater, and M.P. Russelle. 2010. Understanding the variability in nitrogen fixation across agroecosystems. *Plant and Soil* 329(1): 379–397.

Shipley, C. 2000. *Cause and Correlation in Biology: A User's Guide to Path Analysis, Structural Equations and Causal Inference*. Cambridge University Press: Cambridge, UK.

Stehfest, E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eickhout, and P. Kabat. 2009. Climate benefits of changing diet. *Climatic Change* 95: 83–102.

Stronge, K.M., S.D. Lennox, and R.V. Smith. 1997. Predicting nitrate concentrations in Northern Ireland rivers using time series analysis. *Journal of Environmental Quality* 26(6): 1599–1604.

Speelman, E.N., S. López-Ridaura, and N. Allana. 2007. Ten years of sustainability evaluation using the MESMIS framework: Lessons learned from its application in 28 Latin American case studies. *International Journal of Sustainable Development and World Ecology* 14(4): 345–361.

Taylor, M.E., and M.D. Morecroft. 2009. Effects of agri-environment schemes in a long-term ecological time series. *Agriculture, Ecosystems, and Environment* 130(1–2): 9–15.

Teasdale, J., and M. Cavigelli. 2010. Subplots facilitate assessment of corn yield losses from weed competition in a long-term systems experiment. *Agronomy for Sustainable Development* 30(2): 445–453.

Teasdale, J.R., R.W. Mangum, J, Radhakrishnan, and M.A. Cavigelli. 2004. Weed seedbank dynamics in three organic farming crop rotations. *Agronomy Journal* 96(5): 1429–1435.

Thomassen, M.A., R. Dalgaard, R. Heijungs, and I. de Boer. 2008. Attributional and consequential LCA of milk production. *The International Journal of Life Cycle Assessment* 13(4): 339–349.

van der Werf, H.M.G., J. Tzilivakis, K. Lewis, and C. Basset-Mens. 2007. Environmental impacts of farm scenarios according to five assessment methods. 2007. *Agriculture, Ecosystems, and Environment* 118(1–4): 327–338.

Vaylay, R., and E. van Santen. 2002. Application of canonical discriminant analysis for the assessment of genetic variation in tall fescue. *Crop Science* 42: 534–539.

Velicer, W.F., and J.L. Fava. 1998. Effects of variable and subject sampling on factor pattern recovery. *Psychological Methods* 3:231–251.

Wackernagel, M., and W. Rees. 1995. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers: Philadelphia, PA.

Wackernagel, M., L. Onisto, P. Bello, A. Callejas Linares, I. López Falfán, J. Méndez García, A. Suárez Guerrero, and G. Suárez Guerrero. 1999. National natural capital accounting with the ecological footprint concept. *Ecological Economics* 29(3): 375–390.

Wackernagel, M. 2009. Methodological advancements in footprint analysis Introduction. *Ecological Economics* 68: 1925–1927.

Wada, Y., "The Appropriated Carrying Capacity of Tomato Production: Comparing the Ecological Footprints of Hydroponic Greenhouse and Mechanized Field Operations" (master's thesis, School of Community and Regional Planning, University of British Columbia, 1993): http://hdl.handle.net/2429/1526.

Wander, M. M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. *Soil Science Society of America Journal* 63: 961–971.

5

CHAPTER 5

Implementing a Systems Research Project: Troubleshooting and Putting it All Together

Progress is made one step at a time. Every big accomplishment is a series of little accomplishments.
—David Joseph Schwartz

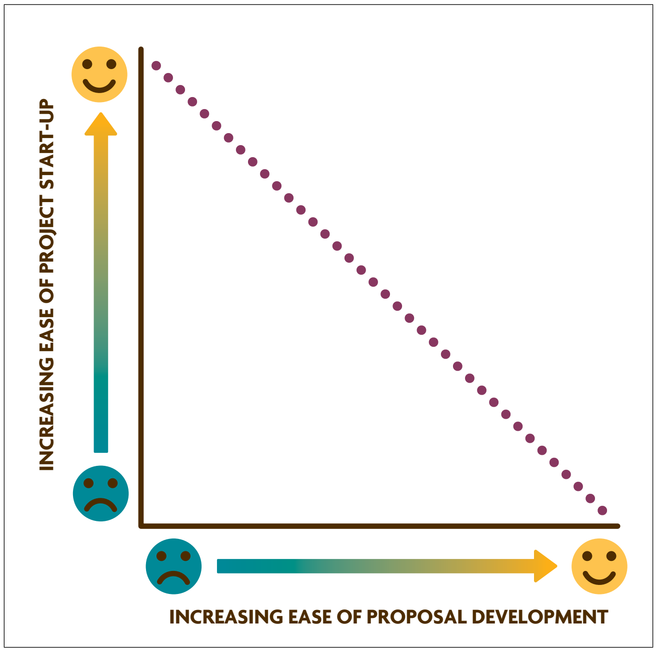
The strategies discussed in previous chapters are the foundation of effective agricultural systems research, and they provide the basis for this final chapter on how to carry out systems projects. This chapter ties together key aspects of implementing a systems project, including planning and start-up, financial management and organizational structure, and it provides advice on troubleshooting.

Starting a Systems Project

The transition from a potential project to one that is successfully implemented requires diligent application of participatory principles. During this start-up phase, the team will revisit the proposal plan and revise it as needed to move into execution. Once funding has been obtained, the team is committed to a collaborative endeavor that will be part of each member's work life for the next few years. It is not surprising that the moment of success is often mixed with conflict and stress. During this transition, many newly formed teams encounter the "storming" phase of team development as described by Tuckman (1965) and discussed in chapters 2 and 3.

Frequently, groups that experienced smooth proposal development will now find that more extensive planning and team development is needed before project implementation can begin (Figure 5.1). Two dynamics contribute to this pattern. First, during the early stages of team development, group members are more likely to defer to the project leader or acquiesce to the dominant viewpoint without voicing divergent opinions (Wheelan, 1994). Second, fully integrating members' diverse perspectives requires more time than was needed during the conceptual stage.

FIGURE 5.1. **Inverse Relationship Between Ease/Time Investment During Proposal Writing and Start-Up Phase**



Groups that avoid conflict during planning and proposal writing often reach the storming phase once funding is received and they begin planning for implementation. In contrast, some groups face challenges during proposal writing and invest more time in resolving differences of opinion before funding is received.

Confirming the Plan and Launching the Project

Upon receiving news of a grant award, begin by confirming the agreements made during the proposal-writing stage and by carrying out a more detailed planning phase. Depending on how long it has been since the proposal was written, changes in circumstance may have occurred that affect the budget, project activities or individual collaborators. The team may find details that were not addressed during the initial stages and that must be resolved to implement the project. If proposal reviewers identified concerns or made recommendations, consider these items carefully; they may improve the project, even if changes are not required by the funder.

Consider the following questions at this stage:

- *Does the conceptual model adequately describe the system?* Check that each collaborator can pinpoint their location within the conceptual model and that farm operator members can validate the system model. Are all important processes included and are there clear boundaries?
- *Are the questions outlined in the proposal still germane?* Have there been any significant changes or discoveries since the proposal was written? Do the questions need to be updated? Do the system-level hypotheses still make sense to the farmers?
- *How well is the decision-making structure working?* Evaluate the decision-making process that occurred during the proposal writing stage. Now that your team is shifting from project development to implementation, how will it make different kinds of decisions? The team may decide to restructure to better fit the implementation phase. For example, if there are more than four to five collaborators, consider reorganizing into subgroups with differing responsibilities.
- *Is the budget allocated appropriately?* Deal with this issue swiftly so the grant contract can be processed. Consider whether there have been any major changes since writing the proposal that would affect the budget. For example, have any collaborators received funding for components that overlap with the larger project? Have there been any significant increases (or decreases) in the costs of budgeted items? If the project was funded at a reduced level, several approaches can be used to reallocate funds. These are discussed under financial management later in this chapter.
- *Can all team members still take on their commitments and tasks as planned?* Check that each collaborator is still committed to their plan of work. Ask each person whether any changes in circumstances have occurred that might make it difficult to follow through with their commitments to the project.
- *Is the timeline confirmed, or does it need to be revised?* Most proposals require a timeline for key tasks. Check whether everyone is in agreement with the timeline. Confirm that agreements are in place for meeting project objectives.

As a team, carefully consider how much planning will be needed to begin implementation, and allocate time for this. The planning period can require anywhere from two to eight months, depending on the size and complexity of the project and the degree of plan modification that is needed. Organize hiring of staff and graduate students to coincide with the time when project activities will be carried out.

Financial Management

From an institutional perspective, the financial management of multidisciplinary systems projects is essentially the same as for other externally funded projects. Normal accounting and budgeting procedures can easily accommodate systems projects, even those with a large number of subcontracts. However, the complexity of systems projects and the need for group decision-making create distinct issues for managing the budget.

Dealing with a Reduced Budget

Research proposals are often not funded at the level of the budget request, and systems projects are no exception. Ideally, the project team will have identified lower-priority components or will have discussed scaled-down versions of the project before a funding decision is made. However, meeting proposal deadlines is stressful, and most teams do not spend time on these hypothetical issues until they receive funding. How can the newly formed team make cuts with the least amount of conflict?

One common approach is to require a flat reduction of all budgets; in other words, each co-PI cuts their budget by an equal percentage and plans for a corresponding reduction in their activities. This approach can work well when the budget reduction is 10 percent or less. It can still work with reductions up to 20 percent, but making significant cuts across the whole project requires care to avoid undermining collaborators who have more fixed responsibilities. For example, it may be difficult to produce 80 percent of an educational product. Also, for collaborators who had a very small budget to begin with, a 20 percent reduction can make it difficult to continue to participate, particularly for nonacademic partners. Some teams opt for a modified version of this procedure that assesses a smaller reduction on collaborators with smaller budgets (e.g., those with less than $30,000 reduce their budgets by 10 percent while everyone else applies a 20 percent budget cut). This allows for adjustment and accommodation of different participants while avoiding the difficult process of weighing project priorities.

A more selective approach to budgeting is often needed, especially for reductions greater than 15 percent. In some cases, the review panel will provide feedback that helps to identify parts of the project as high or low priority. The funding agency may provide guidance in developing a revised plan, especially if the budget reduction is major. This will ensure that the revised project fits the expectations of the funding agency and can reduce the potential for conflict by shifting the responsibility for making cuts away from the team. When budget reductions are moderate (20 to 30 percent), reallocate funds based on group discussions of priorities and options for project redesign. If the team is still forming, conduct this process as openly as possible so that everyone can feel the rebudgeting was fair. Project leaders play an instrumental role in this first crucial decision, which will set the tone for the work that follows. In very large projects with multiple subcontracts, project leaders can work with smaller groups to identify possible cuts and then vet these ideas with the whole team.

If the project has been awarded support with a major reduction, the reallocation process can cause major conflict, especially if some components are eliminated and some collaborators are left without funding. Some large systems projects have been funded at a mere 25 to 50 percent of the requested budget, and implementing such large cuts can cause irreversible damage to a new collaborative team. Groups that have worked together previously and have become an established team are more likely to weather major budget cuts.

Instituting Accountability

Systems projects take place over many years, pass through many stages of development and progress, and draw together team members whose level of investment can vary significantly. Given all of this, issues with accountability are not unusual. To maintain momentum and follow-through, hold regular meetings to assess progress and set target dates for achieving objectives. Commitments made to colleagues in a face-to-face meeting can go a long way toward motivating people to complete tasks on time. Assure that expenditures are matched by progress; this is key to ensuring that collaborators meet their objectives in a timely manner.

Problems with follow-through most often occur when a collaborator does not receive any funding to support his or her involvement in the project. Despite the best intentions, it is almost impossible to guarantee completion of a task for which there is no funding. Besides considerations of basic fairness, collaborators who receive funding tend to feel more ownership toward the project and to have more at stake in a successful outcome. Nonacademic collaborators usually do not have alternate sources of salary support, so funding is directly related to accountability for these team members. If the grant was not structured such that funding matches expected outcomes, the only recourse for ensuring follow-though is persuasion and peer pressure, which can be a shaky proposition. Issues of accountability are less common when collaborators are funded, but they do occur and are often a result of changes in circumstances between the proposal writing and funding stages.

When issues arise due to lack of follow-through, have the project leader respond swiftly by meeting one-on-one with the individual who is not fulfilling his or her commitments. Use this meeting as an opportunity to find out why the work is not progressing, and focus the conversation on problem solving. If the problem cannot be resolved quickly, it may be best for the project and everyone involved if the individual withdraws from the project. In that case, engage another collaborator to carry out the work while sufficient time and resources remain. To create an environment that fosters accountability:

- Develop a well-defined decision-making process and maintain a collegial environment.
- Develop timelines with target dates for specific outcomes.
- Hold regular meetings that include brief progress reports; assign action steps and agree on when commitments should be completed.
- Conduct interim assessments to see that expenditures coincide with expected progress. This may be especially important for nonacademic collaborators who rely on the grant for salary to carry out the planned activities.
- Adjust the timeline when targets are missed.
- Check in with individuals who delay progress to make sure they will meet the revised deadline.
- Delegate responsibility for monitoring progress to several individuals to help the team stay on task.

From the funder's perspective, the responsibility for carrying out a successful project usually lies with the team leader (project director or principle investigator) and his or her organization. This person is generally required to sign off on invoices, including those from subcontracts, so he or she can refuse to sign invoices if repeated efforts have failed to get a collaborator to follow through on commitments. Take this extreme measure only after all other approaches have failed, and consider bringing in a mediator or qualified person from the grants and contracts office to assist in resolving the situation.

Expanding The Project Team

Small teams commonly receive funding to expand projects established through successful collaboration. Project expansion can occur in a variety of ways. The most integrated scenario aims to include new collaborators as full team members; ideally, make this type of expansion coincide with a new grant-writing cycle. Allow plenty of time for adding members, and be willing to adjust the research questions so that they reflect the expertise of new team members. Some of the more common scenarios where this might occur include:

- *A new discovery leads to the need for focused expertise*: The project makes an unexpected discovery outside of the planned lines of research that will be important for understanding the system. In this situation, recruit someone with the appropriate expertise to take on the work.
- *Maximizing outcomes from a systems project*: Systems projects often produce data or samples that can be used to address questions beyond the expertise of the research team. For example, Moss et al. (2004) describe how the Rothamsted experiments have contributed to understanding weed ecology, although that was not the purpose of the experiments. In such situations, the new collaborator may not need to join the project team. Instead, they may agree to analyze samples or data and to coauthor publications without becoming involved as a full collaborator. This can be a mutually beneficial arrangement in which the team expands the information generated by their project, and the collaborator benefits without making the time commitment that would be required of a full team member.
- *Serendipity, or taking advantage of opportunities as they present themselves*: Occasionally, an opportunity for new collaboration presents itself before plans are in place to expand the project. For example, a new faculty member with a research interest well suited to an existing project may join the institution or meet a team member at a professional conference.

Publishing Interdisciplinary Systems Work

As the application of systems approaches to agriculture has become more widespread, it has become easier to find journals that will publish the outcomes of this research. Many journals routinely publish agricultural systems work. Furthermore, publications that favor experiments isolating cause-and-effect relationships have expanded their coverage to include different types of systems-based research.

Begin planning for publication in the very early stages of the project, particularly if collaborators need to publish to receive favorable performance evaluations. Try to ensure that everyone who needs to be a first author has the opportunity to do so. This can be challenging in a complex project, so develop clear criteria for authorship that the research team agrees on. Consider using the following steps to determine authorship:

- Before addressing the details of authorship for specific papers, have an open discussion about authorship in general as it applies to the team, including a discussion of cultural norms within disciplines. The ranking and expectations of authorship can vary across disciplines; make sure that everyone becomes familiar with such differences.
- Sketch out and provide an approximate time line for the expected papers from each major section of the project.
- Identify the first author for the most straightforward cases (e.g., graduate student subprojects, components that have a clear leader).
- For projects that have an identified lead author, add the expected coauthors without determining the sequence. It usually becomes easier to determine the order of co-authors as the work progresses. When several coauthors have made equal contributions, use alphabetical listing.
- Discuss the remaining papers and determine who will contribute to the work. When assigning first authorship, consider the usual factors (e.g., level of contribution, expertise, career stage) as well as the overall distribution of authorship within the project.
- As the work progresses, revisit authorship agreements and make adjustments as needed to reflect actual contributions and avoid misunderstandings.
- As with any other type of jointly authored publication, clearly spell out the responsibilities of each author during the writing stage.

References

Moss, S.R., J. Storkey, J.W. Cussans, S.A.M. Perrryman, and M.V. Hewitt. 2004. The Broadbalk long-term experiment at Rothamsted: What has it told us about weeds? *Weed Science* 52: 864–873.

Tuckman, B.W. 1965. Development sequences in small groups. *Psychology Bulletin* 63: 384–399.

Wheelan, S.A. 1994. *Group Processes: A Developmental Perspective*. Allyn and Bacon: Sydney, Australia.

Journals that Publish Articles on Agricultural Systems Research

Agriculture, Ecosystems and Environment

Agronomy Journal

Ecology and Society

Ecological Applications

Ecosystems

Human Ecology

International Journal of Agricultural Sustainability

Journal of Environmental Quality

Journal of Sustainable Agriculture

Nutrient Cycling in Agroecosystems

Organization and Environment

Renewable Agriculture and Food Systems

Society and Natural Resources

Weed Science

Conclusion

In this handbook, we hope we have laid out in clear and simple terms the best information available on how to conduct agricultural systems research—from basic agricultural systems theory and background, to building collaborative teams, to designing and analyzing research projects.

For every bit of information we have provided, however, there is much more to learn, so please keep the following points in mind:

- Agricultural systems research is an emerging methodology, and new techniques and approaches are developed every day. Stay up to date on the literature and keep an ear out for innovations from the field, including those from farmers and extension. Consider publishing papers on methods that have worked well in your project if they are not already covered in the literature!
- Certain aspects of systems research are applicable across experiments, but each systems experiment is unique, including its boundaries, team composition, questions asked, data analyzed and final integration of results.
- As you build teams of researchers, farmers and other stakeholders, consider if the project could best be carried out by a well-balanced team of biophysical and social scientists. If so, spend some time at the very beginning recruiting across the biophysical–social divide. If your group represents only biophysical disciplines, reach out to social scientists and food system theorists. Conversely, if you are a group of social scientists, consider how you could address ecological and environmental aspects by recruiting biophysical expertise.
- Explore SARE resources at www.sare.org, which contains a vast database of projects, reports and papers summarizing SARE-funded work. Many projects under the Research and Education category have involved multidisciplinary and interdisciplinary research teams with a large array of stakeholders.
- Explore other funding sources for agricultural systems research, such as those mentioned in the introduction of this manual.

Agricultural systems research can be rewarding on many levels. Because every project is unique, there may be no direct precedent for the challenges you encounter, so it will be up to you and your team to find a solution. You will have the opportunity to improve your management and teamwork skills, and you will likely learn a great deal by collaborating with partners from other disciplines and professions. Agricultural systems research is a powerful method for solving complex problems and revealing innovative farming techniques that can have a profound impact on farmers, society and the environment. By establishing or joining a systems-oriented project, you are embarking on a true journey of discovery in both your research and your professional career.

We firmly believe that reading this book is the first bold step toward making meaningful changes in how you approach research and partnerships.

As they say, the rest is up to you.

Additional Resources

Chapter 1

Agricultural Systems: Agroecology and Rural Innovation for Development. 2008. Snapp, S., and B. Pound, eds. Elsevier: Burlington, MA. Geared more toward international agricultural development, this book covers a wide range of topics related to ecological applications that support agricultural sustainability and stakeholder participation in problem-solving and innovation.

The Ecological Knowledge System. 1998. Roling, N.G., and J. Jiggins. In *Facilitating Sustainable Agriculture,* ed. N.G. Roling, and M.A. Wagemakers, pp. 283–311. Cambridge University Press: Cambridge, UK. This chapter outlines a rationale and framework for understanding the policy, institutional, and behavioral changes necessary for transition to sustainable agriculture. The method emphasizes that ecologically sound agriculture requires change not only at the farm level but also at higher agroecosystem levels such as watersheds and landscapes, and that interactive learning among stakeholders fosters the required innovation.

Ecology in Agriculture. 1997. Jackson, L.E., ed. Academic Press: San Diego, CA. A compilation of chapters by various authors provides examples of the application of ecological theory to agricultural systems. Ecophysiology and population and community ecology are discussed by several authors with distinct perspectives on these fields and their application to agriculture.

Farmer First: Farmer Innovation and Agricultural Research. 1989. Chambers, R., A. Pacey, and L.A. Thrupp, eds. Intermediate Technology Publications: London. A landmark publication that documents and characterizes farmers' capacities for innovation and their potential for assuming leadership roles in agricultural research in small farming systems throughout the world.

The Farming Systems Research and Extension Approach to Small Farmer Development. 1990. Baker, D., and D. Norman. In *Agroecology and Small Farm Development*, ed. M. Altieri and S. Hecht, pp. 91–104. CRC Press: Boca Raton, FL. This chapter provides a detailed review of the farming systems research (FSR) approach and an assessment of its contribution to understanding and advancing small farmer development strategies throughout the world. It includes examples of FS projects and programs and highlights factors that limit the potential of this approach.

The Farming Systems Trial: The First Fifteen Years. 1999. Peterson, C., L.E. Drinkwater, and P. Wagoner. Rodale Institute: Kutztown, PA. An interpretive overview of the cropping systems experiment at Rodale Institute, including its design and a survey of results.

Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality. 1998. Cavigelli, M.A., S.R. Deming, L.K. Probyn, and R.R. Harwood, eds. Michigan State University Bulletin E-2646: East Lansing, MI. This extension bulletin gives a nice overview of applied ecology in a production context.

Implementation of long-term agricultural systems studies: challenges and opportunities. 2002. Barbercheck, M.E., M. Bell, C. Brownie, N.G. Creamer, S. Hu, L. Kin, H.M. Linker, F.J. Louws, M. Marra, J.P. Mueller, C.W. Raczkowski, D. Susko, and M.G. Wagger. *HortTechnology* 12: 362–368. An overview of how the systems experiment at North Carolina State was established.

Michigan Field Crop Pest Ecology and Management. 2000. Cavigelli, M.A., S.R. Deming, L.K. Probyn, and D.R. Mutch, eds. Michigan State University Bulletin E-2704: East Lansing, MI. Follows the previous bulletin and focuses on pest management in field crops.

Organic Farming: The Ecological System. 2009. Francis, C., ed. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America: Madison, WI. This book includes chapters that explicitly discuss the role of ecological processes in organic farming systems

Principles of Terrestrial Ecosystem Ecology. 2002. Chapin, F.S., III, R.A. Matson, and H.A. Mooney. Springer-Verlag: New York, NY.

Chapter 2

Collaborative Culture

Explicit knowledge structures as a tool for overcoming obstacles to interdisciplinary research. 2005. Boulton, A.J., D. Panizzon, and J. Prior. *Conservation Biology* 19: Article 6. This paper provides detailed information with examples for using knowledge structures to foster interdisciplinary communication.

How to Make Collaboration Work: Powerful Ways to Build Consensus, Solve Problems, and Make Decisions. 2002. Straus, D. Berret-Koehler Publishers: San Francisco, CA. This concise, inspired, and easy-to-read book is well organized and clearly explains the principles and practices that support collaboration, as well as its benefits. The book is divided into three parts: (1) Fundamentals of human problem solving, (2) Principles of collaboration, and (3) Putting it all together.

Interdisciplinary research: Maintaining the constructive impulse in a culture of criticism. 1999. Pickett, S.T.A., W. R. Burch Jr., and J.M. Grove. *Ecosystems* 2: 302–307. A short essay highlighting some of the challenges faced in planning synthetic interdisciplinary projects. The authors give some useful advice.

Making Collaboration Work. 2000. Wondolleck, J.M., and S.L. Yaffee. Island Press: Washington, DC. This book on collaboration in natural resource management focuses on how to extend decision-making to broad groups of stakeholders. It may be especially useful in thinking about how to engage different demographics in a research program to help ensure long-term support and impact.

Practicing interdisciplinarity. 2005. Lele, S., and R.B. Norgaard. *BioScience* 55: 967–975. Excellent review article that identifies barriers to collaboration across the biophysical–social science divide and provides some possible solutions to overcoming these challenges. Clear and insightful treatment of the subject.

Team Building

The Art and Science of Leadership. 1997. Clark, D. www.nwlink.com/~donclark/leader/leader.html. A comprehensive leadership guide that covers all the basics including theory and practice. Highly recommended!

The Complete Facilitator's Handbook. 1999. Heron, J. Kogan Page: London. This heavily referenced, well-indexed 400-page volume will interest those who aim to become proficient in the theory and practice of facilitation and would be a useful reference for anyone wanting to enhance their skills.

Facilitator's Guide to Participatory Decision-Making, Third Edition. 2014. Kaner, S., L. Lind, C. Toldi, S. Fisk, and D. Berger. Jossey-Bass: San Francisco, CA. This is the most useful book on facilitation that we have come across. We highly recommend that you secure a copy, read it through, and keep it close by for easy reference.

Groups That Work (and Those That Don't): Creating Conditions for Effective Teamwork. 1990. Hackman, J.R. Jossey-Bass: San Francisco: CA. This is a rich and authoritative work, though not a quick and easy read. Think of it more as a text or reference book, for those who want to understand team building in some depth. We highly recommend the introductory chapter, "Work teams in organizations: An orienting framework," for gaining a fundamental understanding of what a work team is and what it can do.

Teamwork: What Must Go Right, What Can Go Wrong. 1989. Larson, C.E., and F.M.J. LaFasto. Sage Publications: London. This research-based yet highly accessible work elaborates eight characteristics that explain how and why effective teams develop. It provides a useful reference for those designing, managing, and participating in teams.

When Teams Work Best. 2001. LaFasto, F.M.J., and C.E. Larson. Sage Publications: London. This practical guide to success in collaborative teamwork is an exceptionally user-friendly resource that provides a one-page "snapshot" of points to remember about each topic addressed. It is alive with case studies and simple graphics that add context to the concepts.

Chapter 3

Amish Dedication to Farming and Adoption of Organic Dairy Systems. Re-Thinking Organic Food and Farming in a Changing World. 2014. Brock, C., and B. Barham. The International Library of Environmental, Agricultural, and Food Ethics. Vol. 22.

Comparative study of organic and conventional tomato production systems: An approach to on-farm research. 1991. Shennan, C., L.E. Drinkwater, A.H.C. van Bruggen, D.K. Letourneau, and F. Workneh. In *Alternative Agriculture, part 2*, ed. J.P. Madden, pp. 109–132. National Academy Press: Washington, DC. Describes how a multidisciplinary team handled the experimental design for a study comparing distinct management systems.

Farm structural change of a different kind: Alternative dairy farms in Wisconsin: graziers, organic and Amish. 2009. Brock, C., and B. Barham. *Renewable Agriculture and Food Systems* 24(1): 25–37.

Landscape-level variation in soil resources and microbial properties in a no-till corn field. 2005. Cavigelli, M.A., L.L. Lengnick, J.S. Buyer, D. Fravel, Z. Handoo, G. McCarty, P. Millner, L. Sikora, S. Wright, B. Vinyard, and M. Rabenhorst. *Applied Soil Ecology* 29: 99–123. Provides an excellent example of how to conduct a spatial analysis in preparation for laying out a large cropping systems experiment.

Methods in Ecosystem Science. 2000. Sala, O.E., R.B. Jackson, H.A Mooney, and R.W. Howarth. Springer-Verlag: New York, NY. Covers techniques commonly used to study carbon and energy dynamics as well as nutrient and water dynamics at the ecosystem scale, and gives examples of how to design manipulative ecosystem experiments. Detailed information about various methods will help researchers choose those most appropriate for their particular studies.

'Milk is milk': Organic dairy adoption decisions and bounded rationality. 2013. Brock, C., and B. Barham. *Sustainability* 5(12): 5416–5441.

Writing Successful Science Proposals. 2000. Friedland, A.J., and C.L. Folt. Yale University Press: New Haven, CT. Does not explicitly address collaborative work but does contain abundant useful information for proposal writing.

Chapter 4

Analysis of Ecological Communities. 2002. McCune, B., J.B. Grace, and D.L. Urban. MjM Software Design.

Applied Multivariate Statistical Analysis. 2002. Johnson, R.A., and D.W. Wichern. Prentice-Hall, Inc: Upper Saddle River, NJ.

Assessment of sampling stability in ecological applications of discriminant analysis. 1988. Williams, B.K., and K. Titus. *Ecology* 69: 1275–1285.

Canonical community ordination. Part I: Basic theory and linear methods. 1994. ter Braak, C.J.F. *Ecoscience* 1: 127–140.

Canonical correspondence analysis and related multivariate methods in aquatic ecology. 1995. ter Braak, C.J.F. *Aquatic Sciences* 57: 255–328.

Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. 1986. ter Braak, C.J.F. *Ecology* 67: 1167–1179.

Contingency-Table Analysis of Rain-Forest Vegetation. 1971. Hatheway, H.W. In *Statistical Ecology. Vol. 3,* eds. G.P. Patil, E.C. Pielou, and W.E. Waters. pp. 271–313. Pennsylvania State University Press: University Park, PA.

Detrended correspondence analysis: an improved ordination technique. 1980. Hill, M.O., and H.G. Gauch. *Vegetation* 42: 47–58.

Handbook of Ecological Indicators for Assessment of Ecosystem Health. 2nd Edition. 2009. Jørgensen, S., L. Xu, and R. Costanza, eds. Taylor & Francis, CRC Press: Boca Raton, FL.

Multivariate Analysis in Community Ecology. 1982. Gauch, H.G. Cambridge University Press: Cambridge, UK. A very well-written and easy to read text. Great introduction into multivariate methods in community ecology. Provides purposes of the described analyses, and examples and criteria for evaluation of the method.

Multivariate analysis in ecology and systematics: panacea or Pandora's box. 1990. James, F.C., and C.E. McCulloch. *Annual Review of Ecology and Systematics* 21: 129–166. Excellent overview of some of the pitfalls of using multivariate methods inappropriately.

Multivariate Analysis of Ecological Data using CANOCO. 2003. Leps, J., and P. Smilauer. Cambridge University Press: Cambridge, UK.

Multivariate Analysis (Probability and Mathematical Statistics). 1980. Marida, K., J.T. Kent, and S. Holmes. Academic Press: San Diego, CA.

Multivariate Statistical Methods: A Primer, Third Edition. 2004. Manly, B.F.J. Chapman and Hall/CRC Press: Boca Raton, FL. Helpful resource for those who have limited or no experience with multivariate statistics.

Multivariate Statistics for Wildlife and Ecology Research. 2002. McGarigal, K., S.A. Cushman, and S. Stafford. Springer-Verlag: New York, NY. Helpful resource for those who have limited or no experience with multivariate statistics.

Non-parametric multivariate analyses of changes in community structure. 1993. Clarke, K.R. *Australian Journal of Ecology* 18: 117–143.

An ordination of the upland forest communities in southern Wisconsin. 1957. Bray, J.R., and J.T. Curtis. *Ecological Monographs* 27: 325–349.

Principal Component Analysis, 2nd ed. 2002. Jolliffe, I.T. Springer-Verlag: New York, NY.

Putting things in even better order: the advantages of canonical correspondence analysis. 1993. Palmer, M.W. *Ecology* 74: 2215–2230.

Reciprocal averaging: an eigenvector method of ordination. 1973. Hill, M.O. *Journal of Ecology* 61: 237–249.

Statistical Analysis of Regional Yield Trials: AMMI Analysis of Factorial Designs. 1992. Gauch, H.G. Elsevier Science Publishers: Amsterdam. Thorough and authoritative text on the AMMI model.

Chapter 5

Project Management Step-by-Step. 2002. Richman, L.L. Amacom: New York, NY. pp 21. Some useful ideas for planning and carrying out a complex project.

Project Management for the Technical Professional. 2001. Dobson, M.S. Project Management Institute. This book provides guidance to help technical professionals develop the necessary skills to succeed in leadership positions. Although the book is geared towards the business world, the first section provides a useful discussion of the difference between doing technical work and managing a technical project.

Visualizing Project Management, 2nd edition. 2000. Forsberg, K., H. Mooz, and H. Cotterman. Wiley and Sons, Inc.: Hoboken, NJ. Written by a trio of authors whose combined project management experience is unequaled in the field. The processes and techniques in this landmark book have been confirmed through the experiences of thousands of working project managers in a variety of corporations. The integrated approach presented in Visualizing Project Management is accessible and complete. This book gets very good reviews.

Additional Readings on Social Science for Systems Research

Agrarian dreams: The Paradox of Organic Farming in California. 2004. Guthman, J. University of California Press: Berkeley, CA.

Agroecology: The Science of Sustainable Agriculture. 1995. Altieri, M.A. Westview Press: Boulder, CO.

Alternative Food Networks: Knowledge, Practice, and Politics. 2011. Goodman, D., E.M. DuPuis, and M. Goodman. Routledge: London and New York.

Are local food and the local food movement taking us where we want to go? Or are we hitching our wagons to the wrong stars? 2011. DeLind, L.B. *Agriculture and Human Values* 28: 273–283.

Brewing Justice: Fair Trade Coffee, Sustainability, and Survival. 2007. Jaffee, D. University of California Press: Berkeley, CA.

Civic Agriculture: Reconnecting Farm, Food, and Community. 2004. Lyson, T.A. Tufts University Press: Medford, MA.

Closing the Food Gap: Resetting the Table in the Land of Plenty. 2008. Winne, M. Beacon Press: Boston, MA.

Coming into the foodshed. 1996. Kloppenburg, J., J. Hendrickson, and G.W. Stevenson. *Agriculture and Human Values* 13(3): 33–42.

Commodity Chains and Global Capitalism. 1994. Gereffi, G., and M. Korzeniewisz, eds. Greenwood Press: Westport, CT.

Cross Continental Food Chains. 2005. Fold, N., and B. Pritchard, eds. Routledge: New York, NY.

Development and Social Change. 1996. McMichael, P. Pine Forge Press: Thousand Oaks, CA.

Food and the Mid-Level Farm: Renewing an Agriculture of the Middle. 2008. Lyson, T.A., G.S. Stevenson, and R. Welsh, eds. MIT Press: Cambridge, MA.

Food for the Future: Conditions and Contradictions of Sustainability. 1993. Allen, P., ed. John Allen Press: New York, NY.

Food is Different: Why we Must get the WTO Out of Agriculture. 2006. Rosset, P. Zed Books: New York, NY.

Food Politics: How the Food Industry Influences Nutrition and Health. 2002. Nestle, M. University of California Press: Berkeley, CA.

Food Security, Sustainability and Nutrition. 2009. Lawrence, G., K. Lyons, and T.C. Wallington, eds. Earthscan: London.

Food Sovereignty: Reconnecting Food, Nature and Community. 2010. Wittman, H. K., A. Desmarais, and N. Wiebe, eds. Food First Books: Oakland, CA.

From Land to Mouth: Understanding the Food System. 1993. Kneen, B. University of Toronto Press: Toronto, Canada.

Hungry for Profit: The Agribusiness Threat to Farmers, Food, and the Environment. 2000. Magdoff, F., J.B. Foster, and F.H. Buttel, eds. Monthly Review Press: New York, NY.

La Via Campesina: Globalization and the Power of Peasants. 2007. Desmarais, A. A. Pluto Press: London.

Locality and Inequality: Farm and Industry Structure and Socioeconomic Conditions. 1990. Lobao, L. State University of New York Press: Albany, NY.

Locating food democracy: Theoretical and practical ingredients. 2008. Hassanein, N. *Journal of Hunger & Environmental Nutrition* 3(2): 286–308.

Mining for justice in the food system: Perceptions, practices, and possibilities. 2008. Allen, P. *Agriculture and Human Values* 25: 157–161.

Remaking the North American Food System: Strategies for Sustainability. 2007. Hinrichs, C.C., and T.A. Lyson, eds. University of Nebraska: Lincoln, NE.

Rights-based food systems and the goals of food systems reform. 2008. Anderson, M. *Agriculture and Human Values* 25: 593–608.

Social sustainability, farm labor, and organic agriculture: Findings of an exploratory analysis. 2006. Shreck, A., C. Getz, and G. Feenstra. *Agriculture and Human Values* 23: 439–449.

Stuffed and Starved. 2007. Patel, R. Portobello Books: London.

Sustainable agriculture in the United States: A critical examination of a contested process. 2010. Constance, D.H. *Sustainability* 2(1): 48–72.

Sustaining the Unsustainable: Agro-Food Systems and the Environment in the Modern World. 2006. Buttel, F.H. In *Handbook of Rural Studies*, ed. P. Cloke, T. Marsden, and P.H. Mooney. pp. 212–229. Sage Publications: London.

The Agrarian Vision: Sustainability and Environmental Ethics. 2010. Thompson, P. University of Kentucky Press: Lexington, KY.

The New Peasantries: Struggles for Autonomy and Sustainability in an Era of Empire and Globalization. 2009. Van der Ploeg, J.D. Earthscan: London and Sterling, VA.

The Violence of the Green Revolution: Third World Agriculture, Ecology, and Politics. 1992. Shiva, V. Zed Books: New York, NY.

Together at the Table: Sustainability and Sustenance in the American Agrifood System. 2004. Allen. P. Pennsylvania State University Press: University Park, PA.

Worlds of Food: Place, Power, and Provenance in the Food Chain. 2006. Morgan, K., T. Marsden, and J. Murdock. Oxford University Press: Oxford, UK.

Index

F

G

H

I

J

K

L

M

N

O

P

R

S

T

U

V

W

Y

Practical information for researchers, educators and extension professionals seeking to understand and apply systems research to agriculture.

Farmers today face a complicated host of environmental, social and economic pressures: protecting water and air resources, mitigating greenhouse gases, conserving biodiversity and limiting soil erosion, all while trying to make a living. These challenges are linked, yet most agricultural research of the last 80 years has approached them from a reductionist standpoint. To build truly sustainable farming systems, agricultural research must embrace a multidimensional approach known as agricultural systems research.

Systems Research for Agriculture outlines both the theory and practice of agricultural systems research, helping agricultural professionals to study, understand and develop economically, socially and environmentally sustainable production systems. This handbook begins with a brief introduction to the theoretical basis for agricultural systems research. It then delivers guidance on how to form effective interdisciplinary and multi-stakeholder teams, which include farmers and ranchers, and how to plan, implement and analyze systems experiments.

This handbook is essential reading for research coordinators and all other team members as they navigate the complexities of multifaceted systems projects.

“*Systems Research for Agriculture* is a valuable contribution to advancing the scientific base of systems research and provides a necessary piece of the multi-dimensional puzzle. The team-building and project-management sections are good nuts-and-bolts pieces that can be used to help maintain the kind of long-term team commitment necessary for systems research.”

–Douglas H. Constance, Professor of Sociology, Sam Houston State University

“*Systems Research for Agriculture* goes beyond theory; it’s truly a handbook–a how-to manual for everything from assembling teams and supporting communication between team members, to designing research and evaluating the results. The practical suggestions for step-by-step implementation and the specific examples of projects that tackled different aspects of systems research are very helpful. This is a much-needed resource.”

–Beth Nelson, Director of Research and Education Programs, North Central SARE

$20.00
ISBN 978-1-888626-16-2
52000>

9 781888 626162