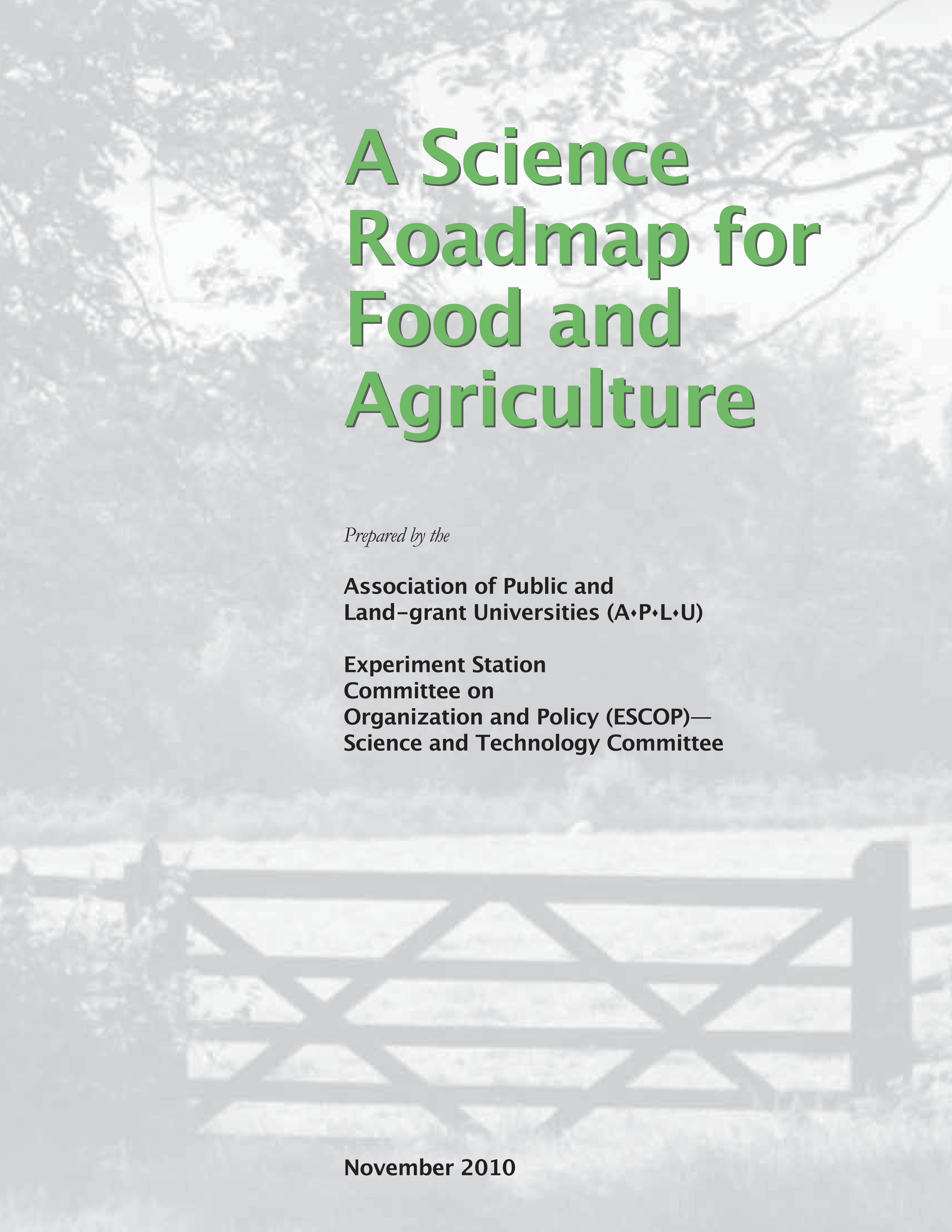

A Science Roadmap for Food and Agriculture

Prepared by the

Association of Public and
Land-grant Universities (A•P•L•U)

Experiment Station
Committee on
Organization and Policy (ESCOP)—
Science and Technology Committee

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Contents

Preamble

I am honored to have been able to provide oversight to the important task of preparing a *Science Roadmap* for food and agricultural research at our land-grant institutions. Many outstanding scientists within our community contributed to this document. This process began with some 250 scientists participating in a Delphi survey that helped to identify research priorities to which our research community could make significant contributions. Once a consensus was formed, seven challenges emerged, and writing teams were assigned to each challenge area. More than 80 scientists were involved in the preparation and review of the seven grand challenge white papers.

The overall document was also reviewed by two long-time leaders in the land-grant system—Drs. Colin Kaltenbach and Daryl Lund—and I want to express my appreciation for their insights and suggestions, and for their long-term guidance on many issues. Finally, my sincere thanks go to our professional editor, Diane Clarke, for her expertise in preparing the final report.

Given the broad and enthusiastic participation in the development of this *Science Roadmap,* I am confident that it will provide critical guidance to academic research administrators and to our federal and private sector partners regarding research directions over the next decade. These efforts will make a difference for the future of our nation relative to how we respond to the seven Grand Challenges. We recognize there are redundancies and differences of opinion among the various sections of the report; this is the nature of science. While the *Roadmap* does not prescribe solutions, it does identify direction and course. More importantly, it is a basis for substantive discussion of concepts associated with, and approaches to addressing, societal issues as they relate to the food, agricultural, and environmental sciences.

I want to thank the many individuals who participated and volunteered time, creativity, and energy throughout this project. Dr. Travis Park of Cornell and other members of the ESCOP Social Sciences Subcommittee provided early guidance to the process used to develop the project. I also want to thank my fellow members of the ESCOP Science and Technology Committee who directly contributed to the project. Finally, this edition of the *Science Roadmap for Food and Agriculture* would not have been completed without the coordination and leadership of Dan Rossi and his fellow Executive Directors of the regional associations of state agricultural experiment stations, including Carolyn Brooks, Mike Harrington, Arlen Leholm, and Eric Young. Their support for this endeavor was essential.

Bill Ravlin
Chair, ESCOP Science and Technology Committee
September 2010

Foreword

The last *Science Roadmap* for the land-grant university system was prepared nearly 10 years ago. There have been many changes in societal needs and priorities over the past decade. The issues of climate change, energy and food security, environmental and economic sustainability, and globalization have moved to the forefront of concerns for the public and for policy makers in the United States. These issues are highly interdependent, and any attempt to address them will require systematic and science-based solutions. Major investments in scientific research as it relates to food and energy production, utilization of natural resources, and development of individuals, families, and communities will be necessary for the United States to remain competitive, sustainable, and socially responsive to its citizens and the citizens of the world.

This *Science Roadmap* is very timely and will be an important resource not only for our academic leadership but also for our public and private partners and advocates. It has been developed through a broad consensus of some of our best scientific leaders. As a roadmap, it does not provide direct solutions to problems; rather, it lays out well-thought-out paths the scientific community can take to reach potential solutions. I am very excited about this major accomplishment and am looking forward to development of the next steps that will be necessary to operationalize its recommendations.

The land-grant university system is indebted to the many faculty members who contributed to this endeavor. Their insights and commitment to the land-grant mission are clearly represented in this document. I thank them and the members of the ESCOP Science and Technology Committee for the contribution of their time and expertise to this project.

Clarence Watson
Chair, ESCOP
September 2010

Introduction

A recently-released Congressional Research Service Report for Congress[1] on agricultural research, education, and extension begins with the following statement:

> Public investment in agricultural research has been linked to productivity gains, and subsequently to increased agricultural and economic growth. Studies consistently find high social rates of return on average from public agricultural research, widely reported to be in the range of 20%-60% annually. Advances in the basic and applied agricultural sciences, such as disease-resistant crop varieties, efficient irrigation practices, and improved marketing systems, are considered fundamental to achievements in high agricultural yields, increases in farm sector profitability, higher competitiveness in international agricultural trade, and improvements in nutrition and human health. Advances in agricultural research, education, and extension have been critical factors affecting the huge agricultural productivity gains seen in the United States after World War II. Agricultural productivity grew on average by about 2%-3% percent annually during the 1950s through the 1980s, but has declined in recent decades.

The report suggests that the recent decline in agricultural productivity gains is at least in part due to declining public investments in agricultural research.

This *Science Roadmap for Food and Agriculture* describes a challenging and exciting future for the nation's land-grant colleges of agriculture and state agricultural experiment stations (SAES). It identifies future directions for research in food and agricultural sciences and makes the case for new investments in research to address the following increasingly complex and pervasive issues:

- An interdependent global economy
- **Climate** variability
- Demands on the environment and the natural resource base
- Renewable bioenergy sources and energy security
- Health care costs
- Trends toward obesity
- Hunger and food security for the world's population
- Challenges to individual, family, and community well-being

A previous *Science Roadmap for Agriculture* was developed in 1998–1999 and published in 2001. It was based on input from disciplinary experts within the land-grant system. That *Roadmap* was updated in 2006, and key challenges and objectives were reviewed again in 2008 based on input from Deans and Directors. The 2001 *Roadmap* provided critical guidance to decision makers in academia and in federal agencies that fund agricultural research.

Many of the issues identified in the 2001 *Roadmap* persist today. However, the context in which these issues occur has changed. Rapid advances in science, changes in societal needs, a changing budgetary environment, and increasing global economic and environmental interdependence justify the comprehensive development of a new *Roadmap*. The title for the new *Roadmap* includes the word "food" to better reflect the broader mission of the land-grant system, one that goes well beyond the traditional definition of production agriculture. It highlights the importance of critical issues such as **food security**, **food safety**, and obesity.

"Agriculture" in the context of this document is defined in its broadest sense and includes food production and associated activities; natural resources including forests, rangelands, wetlands, water, and wildlife; and the affecting social, cultural, and environmental factors.

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[1] Melissa D. Ho. *Agricultural Research, Education, and Extension: Issues and Background* (Congressional Research Service Report for Congress). Washington, D.C., January 6, 2010.

This new *Roadmap* reflects the views of the active land-grant scientific community. The process for developing the *Roadmap* was inclusive, bottom-up, and comprehensive of the issues being addressed by the land-grant system. While it focuses on research priorities, it acknowledges the educational context in which those priorities will be extended to the American public.

The goals of this current *Roadmap* are to:

- Chart the major directions of agricultural science over the next 5 to 10 years.
- Define the needs and set the priorities for research.
- Provide direction to decision makers for planning and investing resources in future program areas.
- Support advocates of the food and agricultural research and education system.
- Support marketing of the SAES system.
- Facilitate the building of partnerships for a stronger coalition to solve problems.

Conceptual Framework

Balancing Research and its Impacts on Society. The land-grant university system, through their colleges of agriculture, Agricultural Experiment Stations, and Cooperative Extension Services, has a long tradition of solving societal problems by balancing strong science with benefits and consequences to society. It can do so because it has the broad disciplinary expertise to address both the bench-science and human dimensions of issues.

This *Roadmap* capitalizes on this capacity. It directs investments into both fundamental and **translational research**. The translational research is integrated with teaching and outreach to effectively address societal needs. For maximum impact the research must be integrated beyond traditional outreach and through to commercialization. Further, strong science needs to serve as the basis for sound agricultural and natural resource policy. It can do so if it is produced in an environment that recognizes its impacts beyond the research laboratory, greenhouse, or field. Both research and education must also be sensitive to the factors that influence adoption, including the **scale dependence** of new technologies.

Taking a Global View and a Systems Approach in Existing and Future Research. This *Roadmap* reflects comprehensive thinking about the future of agricultural sciences. However, it is not an exhaustive description of all agricultural research currently being conducted at land-grant institutions. Many current productive research programs need to be continued and sustained. The *Roadmap* establishes a global view of issues that includes multiple dimensions—e.g., the natural sciences and the environmental, economic, and social dimensions. Research priorities are framed in the context of sustainability, including economic efficiency, environmental compatibility, and social acceptability. In many cases, a systems approach will be necessary to address the multiple dimensions and interrelations among the variables.

Framing the Needs and Identifying the "Grand Challenges." This *Roadmap* is framed around the following societal needs:

- The need for U.S. food and agricultural producers to be competitive in a global environment.
- The need for food and agricultural systems to be economically, environmentally, and socially sustainable.
- The need for U.S. agriculture to adapt to and contribute to the mitigation of the effects of climate variability.
- The need to enhance energy security and support a sustainable **bioeconomy** in the United States.
- The need for safe, healthy, and affordable foods.
- The need to address global food security and hunger.
- The need to be good stewards of the environment and natural resources.
- The need for strong and resilient individual, families, and communities.
- The need to attract and develop the next generation of agricultural scientists.

These needs are reflected in a series of "grand challenges" facing society. For each grand challenge, a series of specific research priorities was identified. However, the grand challenges are highly interdependent, and many of the research priorities may contribute to more than one of the challenge areas. It is also important to note that the grand challenges and corresponding research priorities cut across geographic boundaries. Land-grant university research administrators constantly need to strike a balance among local, regional, national, and global research priorities.

The Roadmap Process

IDENTIFYING CHALLENGE AREAS AND RESEARCH PRIORITIES

In the winter of 2009, the Experiment Station Committee on Organization and Policy (ESCOP), which serves as the governing body of the Experiment Station Section of the **Association of Public and Land-grant Universities**, decided to initiate a new *Science Roadmap*. The task of developing the *Roadmap* was assigned to the ESCOP Science and Technology Committee. The Committee met jointly in March of 2009 with the Social Science Subcommittee and prepared a proposal to initiate development of the *Roadmap* through the use of the Delphi process for identifying and confirming grand challenge areas and respective research objectives. The Delphi process gathers the ideas of experts and moves them and their ideas to consensus. The Science and Technology Committee received approval to engage Dr. Travis Park of Cornell University to conduct the survey process and analyze the data.

ESCOP Chair Steve Pueppke sent a letter to Deans and Directors of Research, Extension, and Academic Programs in the land-grant system, requesting their participation and asking for the nomination of up to five researchers or Extension educators from their institutions to participate in the process. The participating researchers and educators were to have the perspective, experience, and expertise to provide quality input about identifying grand challenges and research priorities for the next 10 years within each of the challenge areas. A total of 457 individuals were nominated from a broad array of institutions and disciplines.

Participants were asked to complete four rounds of Delphi surveying regarding future directions for agricultural research over the next 5 to 10 years. Using information from the previous *Roadmap* as the starting point, participants were asked to identify new research priorities and amend current priorities. The first three rounds involved participants' responses to proposed research priorities presented in a summated rating scale format in which "5" equaled *strongly agree* and "1" equaled *strongly disagree*. The final round consisted of a dichotomous *yes-no* format, in which respondents answered the question of whether or not to include each particular proposed research priority in the updated *Roadmap*.

The first round was initiated on June 10, and 264 individuals participated. More than 100 research priorities were suggested by respondents during the first three rounds. The fourth and final round was completed on August 10 and included 246 participants. A total of 13 grand challenge areas and 64 research priorities were identified.

Recognizing the need to further focus the challenge areas, the ESCOP Science and Technology Committee analyzed the 13 challenges and performed a **crosswalk** of these with agricultural research challenge areas identified by other organizations and agencies. (A summary of this crosswalk process is presented in Appendix A.) As a result of this process, a consensus was formed around the seven grand challenges for food and agriculture presented in this *Roadmap*.

IDENTIFYING HOW SCIENCE CAN CONTRIBUTE

Having identified the seven challenge areas and associated research needs through the inclusive process described above, it was then necessary to analyze these areas and identify how science can contribute to them. For each challenge area, it was necessary to frame the issue, explain its importance, assess current capacity and science gaps, identify research needs and priorities, and describe the expected outcomes of new research investments.

Teams of key scientists from the land-grant system were assigned the task of preparing short white papers for each of the challenge areas. These scientists are leaders in their respective disciplines but also broad thinkers who understand the larger picture. Members of the ESCOP Science and Technology Committee participated on the teams to help provide coordination to the overall effort. Finally, the regional research Executive Directors provided additional support and coordination to the teams. The names of the approximately 50 research scientists and administrators who participated in the preparation of these white papers are listed in Appendix B. The white papers were reviewed by additional scientists to insure accuracy and completeness and were then integrated into a comprehensive document. The document was reviewed by the ESCOP leadership in July 2010 and then by the Experiment Station Research Directors at their annual meeting in September 2010.

The following summarizes the seven challenge areas and their associated research priorities that have been identified for this new *Science Roadmap for Food and Agriculture*.

The Seven Grand Challenges

Challenge 1: We must enhance the sustainability, competitiveness, and profitability of U.S. food and agricultural systems.

Agricultural and food production systems are increasingly vulnerable to rising energy costs, loss of key fertilizer sources (e.g., phosphorus deposits), and climate variability. We need new approaches for ecological management and more energy-efficient agricultural practices to meet food needs, provide sufficient economic returns to producers, and deliver multiple environmental benefits. Our areas of scientific focus should be:

- Developing profitable agricultural systems that conserve and recycle water through
    - innovative methods to capture and store rainfall and runoff
    - use of impaired waters for irrigation
    - development of new crop varieties with enhanced water-use efficiency
    - increased productivity of rain-fed agricultural systems
    - development of livestock grazing systems that have increased flexibility and resiliency to drought
- Developing institutional mechanisms that create incentives for sharing agricultural water and that increase public support for balancing the requirements for food production on the one hand and the life-quality issues of society on the other
- Developing new plant and animal production systems, products, and uses to increase economic return to producers
- Improving the productivity of organic and sustainable agriculture
- Improving agricultural productivity by sustainable means, considering climate, energy, water, and land use challenges

Challenge 2: We must adapt to and mitigate the impacts of climate change on food, feed, fiber, and fuel systems in the United States.

The impacts of climate change and climate variability on agriculture, food systems, and food security will have socioeconomic, environmental, and human health implications. Public and private decision makers need new technologies, policy options, and information to transform agriculture into an industry that is more resilient and adaptive to climate variability and climate change. Our areas of scientific focus should be:

- Improving existing and developing new models for use in climate variability and change studies; addressing carbon, nitrogen, and water changes in response to climate; assessing resource needs and efficiencies; identifying where investments in adaptive capacity will be most beneficial; and addressing both spatial and temporal scale requirements for agricultural decision making
- Developing economic assessments to provide more accurate estimates of climate change impacts and the potential costs and benefits of adaptation, and to validate and calibrate models
- Incorporating advances in decision sciences that could improve uncertainty communication and the design of mitigation and adaptation strategies
- Developing new technologies, including

social networking tools, for more effective communication to selected target audiences
- Identifying appropriate policies to facilitate both mitigation and adaptation, and identifying how these policies interact with each other and with other policies

Challenge 3: We must support energy security and the development of the bioeconomy from renewable natural resources in the United States.

To meet the increasing demands of a growing world population, we must provide renewable energy and other potential bioproducts in an efficient, environmentally-sustainable, and economically-feasible manner. Research is needed to ensure the vibrancy, resiliency, and profitability of our agricultural system and to secure new economic opportunities resulting from the production of energy, fabrics, polymers, and other valuable chemicals in the form of renewable bioproducts from agricultural materials. Our areas of scientific focus should be:
- Developing technologies to improve production-processing efficiency of regionally-appropriate biomass into bioproducts (including biofuels)
- Developing agricultural systems that utilize inputs efficiently and create fewer waste products
- Assessing the environmental, sociological, and economic impacts of the production of biofuels and **coproducts** at local and regional levels to ensure sustainability
- Expanding biofuel research with respect to non-arable land, algae, pest issues that limit biofuel crop yields, and emissions of alternative fuels
- Restructuring economic and policy incentives for growth of the next-generation domestic biofuels industry

Challenge 4: We must play a global leadership role to ensure a safe, secure, and abundant food supply for the United States and the world.

Rapid increases in the world's population, climate change, and natural disasters will challenge the use of natural resources and necessitate concomitant increases in food production, nutritional quality, and distribution efficiencies. New scientific knowledge that enhances food commodities, minimizes contamination, ensures a secure food supply, and supports effective and reasonable regulatory policies will be needed. Our areas of scientific focus should be:
- Developing technologies and breeding programs to maximize the genomic potential of plants and animals for enhanced productivity and nutritional value
- Identifying plant compounds that prevent chronic human diseases (e.g., cancer), and developing and encouraging methods to enhance or introduce these plants and compounds into the food system
- Developing effective methods to prevent, detect, monitor, control, trace the origin of, and respond to potential food safety hazards, including bioterrorism agents, invasive species, pathogens (foodborne and other), and chemical and physical contaminants throughout production, processing, distribution, and service of food crops and animals grown under all production systems
- Developing food supply and transportation systems and technologies that improve the nutritional values, diversity, and health benefits of food and that enhance preservation practices, safety, and energy efficiency at all scales, including local and regional
- Decreasing dependence on chemicals that have harmful effects on people and the environment by optimizing effective crop, weed, insect, and pathogen management strategies

Challenge 5: We must improve human health, nutrition, and wellness of the U.S. population.

Rapidly escalating health care costs, rates of obesity, and diet-related diseases are issues of highest national concern. We need a systematic and multidisciplinary approach to understanding the role of healthy foods and lifestyle in preventing, mitigating, or treating obesity and chronic diseases, including diabetes, arthritis, and certain cancers. Our areas of scientific focus should be:

- Investigating the potential of nutritional genomics in personalized prevention or delay of onset of disease and in maintenance and improvement of health
- Identifying and assessing new and more effective nutrient delivery systems for micronutrients and antioxidants
- Identifying, characterizing, and determining optimal serving size and frequency of intake for health benefits of the consumption of specific foods containing bioactive constituents
- Developing community-based participatory methods that identify priority areas within communities, including built environments, that encourage social interaction, physical activity, and access to healthy foods—especially fruits and vegetables—and that can best prevent obesity in children and weight gain in adults
- Understanding factors, including biological and psychological stresses, that contribute to chronic diseases and the aging processes

Challenge 6: We must heighten environmental stewardship through the development of sustainable management practices.

Management decisions made by agricultural landowners and producers impact not only the food, fiber, ornamental plants, and fuel products of agriculture but also ecosystem goods and services, such as **nutrient cycling**, the circulation of water, regulation of atmospheric composition, and soil formation. Research emphasis must be placed on the interaction between agricultural production practices and their regional and global impacts. Our areas of scientific focus should be:

- Assessing the capacity of agricultural systems to deliver **ecosystem services**, including trade-offs and synergies among ecosystem services
- Reducing the level of inputs and improving the resource use efficiency of agricultural production
- Enhancing internal ecosystem services (e.g., nutrient cycling, pest control, and pollination) that support production outcomes so that chemical inputs can be reduced
- Developing ecologically-sound livestock and waste management production systems and technologies
- Developing systems-oriented and science-based policy and regulation for sustainable agricultural systems

Challenge 7: We must strengthen individual, family, and community development and resilience.

Factors such as globalization, climate change, rapid changes in technology, demographic changes, and new family forms and practices are resulting in increased pressures on today's families. Stress is especially severe among vulnerable populations, including many living in rural communities. Rigorous research must guide the development of a strong and resilient rural America. This research must be balanced and must focus on the ties between community viability and family resilience. It must build understanding of the adjustments occurring in rural areas and the consequences of these changes. Our areas of scientific focus should be:

- Understanding the relative merits of people-, sector-, and place-based strategies and policies in regional economic development and improving the likelihood that rural communities can provide supportive environments for strengthening rural families and spurring a civic renewal among people, organizations, and institutions
- Modeling of poverty risks and outcomes to disentangle the influences of characteristics of poor individuals from the influences of their families, communities, and other organizational and institutional factors
- Understanding how local food systems actually work, particularly for small producers and low-income consumers, and how local food production contributes to the local economy, to social and civic life, and to the natural environment
- Assessing the role of broadband and the accelerated investment being made in broadband penetration in rural America as a community economic development strategy
- Understanding the links among individual behavior, community institutions, and economic, social, and environmental conditions

Conclusion

This new *Science Roadmap for Food and Agriculture* will be essential in its contribution to fulfilling the land-grant mission to extend cutting-edge research to solve critical problems for the public good. It establishes a benchmark for future dialogue around these crucial societal challenges. It provides a justification for continued and even expanded public investment in research in these Grand Challenge areas over the next 10 years.

1

Grand Challenge 1

We must enhance the sustainability, competitiveness, and profitability of U.S. food and agricultural systems.

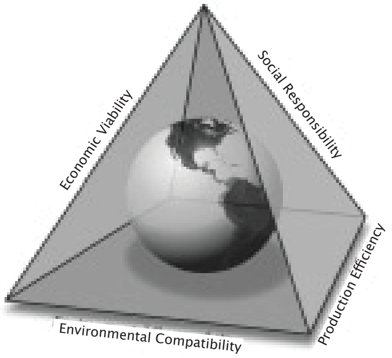


Figure 1. The Ecological Paradigm.

Framing the Issue

The achievement of sustainability, in broad terms, requires striking a balance among social, environmental, and economic dimensions to navigate the many challenges that will be outlined below. This concept is illustrated in the Ecological Paradigm (Figure 1), which was adopted by the College of Food, Agricultural, and Environmental Sciences at The Ohio State University to visualize the strength derived from the collaborative interrelationships among production efficiency, economic viability, social responsibility, and environmental compatibility from local to global scales. Overlooking or omitting consideration of these interdependencies in addressing any one of these dimensions will not provide sustainable pathways.

Sustainable agriculture is neither a philosophical position nor a specific set of practices. Rather, it is a national and global imperative. Although definitions of sustainability abound, common elements include 1) social, environmental, and economic dimensions are thoroughly considered and addressed in a balanced manner, and 2) relevant time scales span generations into the future. Given the degree of complexity that comes with multiple dimensions, and with time frames beyond the careers of most scientists, we require scientific approaches that are based in an understanding of system behavior and long-term change and that deal with uncertainty and unpredictable changes in the environment (Holling 2001). Moreover, beyond static sustainability, agricultural systems must also have resilience—i.e., the ability to adapt to unpredictable changes in the social, political, natural, and physical environments (Folke et al. 2003). This kind of resilience requires anticipating the possibility that the environment could change in unpredictable ways to the extent that existing agricultural production systems would no longer be capable of providing the needs of future generations. Adaptation to such drastic changes would need to be based on all available science and technology (Holling et al. 2002). Assuring the resilience of agriculture thus requires increasing diversity in terms of both human knowledge and biology/genetics to augment and improve the array of building blocks needed to develop new capabilities. The next several paragraphs highlight some of the specific challenges and needs with regard to sustainability, competitiveness, and profitability of food and agricultural systems in the United States.

Environmental challenges to profitability include dwindling cheap fossil fuel supplies, on which current agricultural systems are very dependent, and a changing **climate**, with higher average temperatures and, in many places, less water. Even more critical to profitability are the expected greater extremes in temperature and precipitation, as well as the ongoing struggle to avoid degrading soil and water resources, all of which can affect agricultural productivity. In addition, the realities of higher energy costs and the need for **food security** at continental scales are running counter to recent extremes in globalization of the economy: for any continent, food security, or at least a balance between food exports and imports, is a more likely path to sustainability than reliance on distant and increasingly unreliable sources of this

Sustainability is more than a buzzword. It involves:

- Enhancing environmental quality and the natural resource base upon which the agricultural economy depends
- Enhancing efficient use of nonrenewable and on-farm resources and, where appropriate, integrating natural biological cycles and controls
- Sustaining the economic viability of farm operations and the entire agricultural industry
- Improving the quality of life for farmers, ranchers, and society as a whole
- Providing for adaptive management that can meet climatic changes or other megatrends

basic necessity of life. Given dwindling supplies of cheap transportation fuel, a growing societal emphasis on localization of food systems, and the need for increased self reliance for food at local to regional scales, more opportunities exist for new and sustainable economic activity in locally-focused agriculture than in continuous competition for global exports. In addition, a key impact of investing in local food systems is the beneficial social dimension of reintegrating agriculture into culture, with greater understanding and appreciation among consumers for what it takes to produce food and a greater understanding among producers of what people really want and need. Fostering and maintaining viable communities around farming is a current challenge and key ingredient for sustainable and profitable food and agricultural systems. The role of profitability is critical for farms of all sizes in order to develop food systems that sustain the health of communities, the nation, and natural resources while meeting the many other challenges of this *Roadmap*.

Demographic trends clearly indicate that the global population is becoming more urbanized as well as more concentrated in coastal communities, and these coastal communities are more vulnerable to severe **weather**, rising sea levels, and a lack of fresh water. These trends are accompanied by continued global population growth, with expectations that we will reach a population of 9 billion globally and 440 million in the United States by 2050. Inevitably, these demographic shifts will lead to increased demand for food, energy, water, and sanitation infrastructure to meet society's needs and prevent further environmental degradation. Meanwhile, the urban and **ecosystem** demands of population growth will continue to move water away from agricultural use, increasing production vulnerability and reducing our ability to sustainably meet future global food needs.

The dramatic spike in world food prices and the resulting food riots in 2008 brought into sharp focus not only the interconnected nature of the global economy but also the fragile balance that exists between food supply and demand on the one hand and the threat of hunger on the other. However, the food price increases provided only temporary reprieve for American farmers, who on average continue to earn low economic returns. Recent data indicate a continued hollowing out of agricultural producers "in the middle"—those farmers with annual farm sales of more than $2,500 but less than $1 million (Figure 2).

This trend has important implications not only for the farmers themselves but also for the communities in which they once lived and farmed and thus supported a range of thriving local businesses. Even as total farm numbers continue at a gradual (albeit slowing) rate of decline, in recent decades the nation has been facing the paradox of both rising food insecurity and hunger among vulnerable populations alongside very high obesity rates. While the present unprecedented level of food insecurity in the United States and the attendant demands on public programs such as the U.S. Department of Agriculture's (USDA) Supplemental Nutrition Assistance Program (SNAP) may be the passing result of the current recession, and while rising adult (but not child or minority) obesity rates are projected to stabilize (Basu 2009), it is clear that the average American diet has become less than optimal. In particular, the human, social, and economic costs of obesity are staggering.

The concomitant issues of price, availability, and quality of food and fiber launched the term "sustainable agriculture" in the late 1980s. Today, the concept of sustainability has matured to become an integral part of the agricultural mainstream. Its terminology and research information flow across the landscape, providing fodder for field days, conferences, and the day-to-day work of producing the nation's food, fiber, fuel, and flowers. In the last 20 years, State Agricultural Experiment Station and USDA-Agricultural Research Service (ARS) projects containing references to sustainability, as recorded on the USDA-National Institute of Food and Agriculture (NIFA) Current Research Information System (CRIS), have grown from less than 50 to more than 7,510. In addition, the USDA-NIFA Sustainable Agriculture Research and Education (SARE) program has funded more than 3,000 competitive research and education grants nationwide

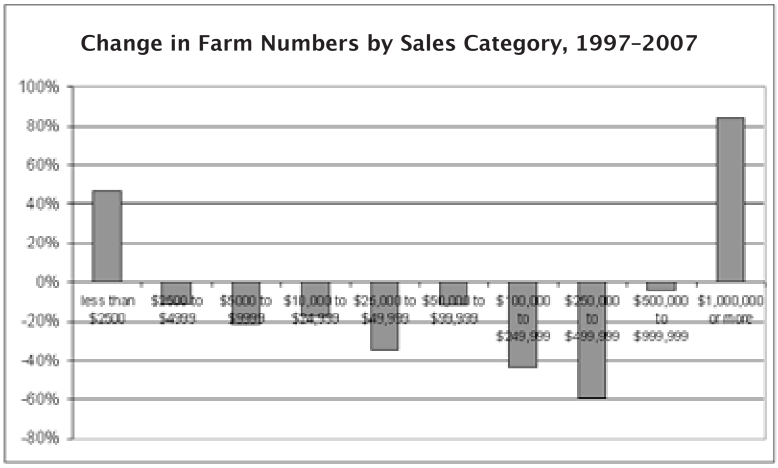


Figure 2. (USDA 2007 Census of Agriculture; adjusted for farm price inflation.)

to producers, scientists, and agricultural support professionals. The resulting techniques and practices have, in turn, been communicated to other producers and agricultural professionals. An exponential spread of new knowledge has resulted, with numerous sustainable benefits, including improved soil, increased adoption of integrated pest management (IPM), reduced pesticide use, higher profit margins, cleaner and more abundant water, stronger local communities, environmentally friendly pest control, improved marketing, and a host of biological cycles and processes that reduce costly inputs into agricultural operations. In spite of these advances, there is an ever-increasing need for further research that centers on the sustainable use of limited high-quality cropland, limited water supplies, critical crop nutrients, and limited energy supplies. There is also a need for research that focuses on preserving and optimizing the genetic resources of plant and animal systems. In addition, more attention must be paid to the off-farm impacts of research-based management practices. Specifically, cutting-edge research must be centered upon the basic principles of sustainability in its broadest sense.

Agriculture consists of many interlinked physical, biological, economic, and human variables.

Current Capacity and Science Gaps

Agriculture needs to be analyzed by looking at the whole system, since agriculture consists of many interlinked physical, biological, economic, and human variables. For example, rather than focusing on the efficiency of production systems entirely in terms of the labor input required, we rely increasingly on methods such as "**life cycle analysis**," which can be employed to evaluate the sustainability of different agricultural production, processing, and distribution systems with respect to their total energy demands and the likelihood of meeting these demands in the future. Likewise, analyzing water use and land use changes on a global scale, as well as their impacts on both the global food system and biodiversity, must be a key component of evaluating sustainability. These system-level approaches are necessary to effectively evaluate how agricultural production systems can and should respond to various population growth scenarios and future food needs. Additionally, such approaches must be available to evaluate and balance multiple and diverse food production systems (both centralized and decentralized), using either economies of scope or economies of scale as the drivers for efficient production. This balance will require well-articulated strategies and techniques for analyzing, describing, and quantifying the many trade-offs inherent in such complex systems with their multiple benefits and costs to various constituencies.

The success of agricultural systems has traditionally been analyzed by employing a narrow focus on productivity alone, based on current policy and energy and labor costs, and utilizing economic returns as the key metric. In order to keep up with the rapid pace of environmental change, and given the fundamentally local nature of agriculture, better approaches and techniques for managing the whole knowledge system are needed. These approaches and techniques must include not only scientific methods for generating new, evidence-based knowledge, but they must also capture practitioners' tacit and local knowledge. Despite the general recognition of the value of holistic and systems approaches for evaluating agriculture, the data and analytical tools for evaluating, comparing, and developing agricultural systems as combinations of interlinked physical, biological, and social variables have not been well developed. Agricultural knowledge continues to accumulate through single-discipline-based research, with less emphasis on well-reasoned and multi- and interdisciplinary strategies aimed at understanding complex system dynamics. Meanwhile, system-oriented research tools currently being developed in engineering, natural resource, and social science fields are continually improving and can provide excellent resources if they are adapted and focused to benefit agriculture. For example, analyses of systems in terms of energy and life cycle assessment require more detailed model development and data before they can be applied to the wide variety of existing agricultural production, processing, and distribution systems. Analyses that produce complete economic accounting of the multifunctional costs and benefits of agriculture are relatively rare. And research on the impacts of agriculture and food systems on global land use change, biodiversity, and production capacity, for example, has not tended to guide policy.

Although improvement of IPM, soil building, and animal and plant management strategies for sustainable production have long been goals of agricultural research, future challenges will require the discovery of additional new approaches for ecological management and more energy-efficient agricultural practices that will meet food needs, provide sufficient economic returns to producers, and deliver multiple environmental benefits. Resilience demands constant innovation to develop new approaches and ways of thinking, and it requires the capacity to communicate and spread innovations quickly in response to unexpected challenges.

WATER RESOURCES WILL PRESENT MAJOR CHALLENGES

Global change and future climate variability are expected to have profound impacts on water demand and supplies, water quality, and flood and drought frequency and severity. Crop and livestock production systems are vulnerable to drought and severe weather events. Increasing the resiliency of these systems will be essential to maintaining productive agricultural systems under changing climate conditions.

Food production currently utilizes more than 70 percent of the total freshwater withdrawals that occur globally, and the percentage is slightly higher than that in the United States. At the same time, urban communities continue to demand a larger share of freshwater. With rivers over-appropriated and major groundwater aquifers being steadily depleted, we are moving toward a significant scarcity of water resources and an increased potential for conflict over those diminished resources. The result is that the projected need, as commonly expressed, to double food production by 2050 must largely be fulfilled on the same land area but with a reduced water footprint.

To meet these challenges, we must develop profitable agricultural systems that both conserve and recycle water. This includes finding innovative methods to capture and store rainfall and runoff, using impaired waters for irrigation, developing new crop varieties that have enhanced water use efficiency, increasing the productivity of rain-fed agricultural systems, and developing livestock grazing systems that have increased flexibility and resiliency to drought. Additionally, new institutional mechanisms must be developed and tested that create incentives for sharing agricultural water and that increase public support for balancing the requirements of food production on the one hand and the life quality issues of society on the other.

Research Needs and Priorities

WATER RESOURCES

- *Water use efficiency and productivity.* Develop crop and livestock systems that require less water per unit of output; systems with increased resilience to both flooding and drought as well as interruptions in supply; institutional arrangements to facilitate water sharing across sectors; and water pricing and other market-based approaches.
- *Groundwater management and protection.* Develop new management and institutional arrangements to sustain groundwater systems, including real-time data networks and decision support systems to optimize conjunctive use of surface water and groundwater. Develop watershed management systems that are

Water problems threatening agricultural sustainability include:

- **Reduced, marginal, and less-reliable water supplies**
- **Water quality problems related to agricultural runoff**

more effective in capturing water during increasingly intense precipitation events and storing it for use during droughts.

- *Wastewater reuse and use of marginal water for agriculture.* Develop cropping systems and irrigation strategies that use impaired and recycled water while protecting soil health and quality; address institutional barriers to the use of non-conventional waters; assess public health issues related to pathogens and heavy metal contamination; explore marginal water treatment technologies and methods to reduce energy requirements for treatment; investigate use of brackish water to supplement freshwater resources; consider new approaches to reduce costs for desalination; and develop salt-tolerant crops.
- *Agricultural water quality.* Develop new approaches to reduce nutrients, pathogens, pesticides, salt, and emerging contaminants in agricultural runoff and sediments; determine socioeconomic barriers to adoption of new water quality practices and develop innovative approaches to encourage and sustain adoption; develop methods for onsite treatment of **tile drainage** water; and explore new methods to reduce water quality impacts from animal waste.
- *Water institutions and policy.* Develop river basin-scale institutional and planning approaches that integrate land use, water, and environmental and urban interests for robust management solutions; investigate policy needs to sustain agricultural water supplies and increase institutional and administrative flexibility.

PLANT PRODUCTION AND INTEGRATED SYSTEMS

On-farm productivity of crops can be improved in a manner similar to that achieved for corn. However, sustained investment is required for research on responsiveness of crops to fertilizer (organic and nonorganic); herbicide and insecticide resistance; drought and frost tolerance; improved hardiness in the face of handling, processing, and shipment; and other important aspects of production, such as mechanical harvesting in the case of certain tree fruits.

Integrated biosystems modeling work that combines economic and biological factors is needed to better understand and fully exploit synergies that may be found by coupling crop and livestock enterprises within the same farm. This represents an important shift away from compartmentalized, discipline-specific research (Gewin 2010), and the returns on such research are potentially significant. Further, significant research needs exist in the bioengineering field for developing composters/digesters and biofuels-based energy generators that allow farmers to sell into the local electricity grid, providing them with additional revenue streams. A sizeable new research frontier has opened up in the area of renewable energy sources that provides potentially important new avenues of income for farmers. Effectively taking advantage of this frontier requires advances in technology as well as new research in the areas of policy, market, and consumer acceptance.

A critical need exists to develop technologies and marketing strategies across different crops that are appropriate for farms operating at vastly differing scales, including the very small to the very large, while not ignoring the vulnerable farms "in the middle." Especially in the case of fruit and vegetable production, opportunities are widely believed to exist on the fringes of urban areas, where access to fresh products is critically important and also perceived to be of high value by consumers. As interest in urban gardening grows (including rooftop and vertical gardens), the need for adaptation of crop production for these venues and the need for **bioremediation** in urban environments are also pressing issues. While important advances have occurred in our understanding of emerging market institutions such as **Community Supported Agriculture** (e.g., Brown and Miller 2008) or Farm-to-School programs (e.g., Schafft et al. 2010), a more science-based understanding of the causes and consequences of these institutions in the wider context of local and regional food systems is urgently needed in light of the concerns about obesity and access to quality food for all segments of the population.

DEVELOP NEW PLANT PRODUCTS, USES, AND CROP PRODUCTION SYSTEMS

- Improve crop productivity with limited inputs of water and nutrients through enhanced efficiencies, plant biology, IPM, and innovative management systems.
- Develop strategies to enhance energy efficiency in agricultural production systems.
- Develop technologies to improve processing efficiency of crop bioproducts (e.g., biofuels, pharmaceuticals, and **functional foods**).
- Investigate the interdependency of multiple land-use decisions, including uses for food, fiber, biofuels, and **ecosystem services**.
- Assess the benefits and costs of decreasing the dependency on synthetic, petroleum-based chemicals in the agricultural industry.
- Conceive new markets for new plant products and new uses for those crops.

ANIMAL PRODUCTION

Domestic livestock, poultry, and aquaculture products make up the major proportion of food consumed in the United States. Advances in agricultural research in the last 40 years have revolutionized the way animals are produced and processed, leading to significant increases in production and substantial improvements in product quality. These advances have often allowed producers to keep up with demand even while reducing their environmental footprint. In recent years, however, a number of challenges have led to reduced profitability, threatening the sustainability of animal agriculture while simultaneously threatening **food abundance**, safety, and security. The leading challenge, the globalization of the world economy, has recast international expectations for food production and transport and created a concomitant change in market patterns. Domestically, recent changes in utilization of grains for bioenergy have created shifts in animal nutrition management and animal production systems, requiring dietary adjustments for food animals that are based on price and availability of grains and grain products (e.g., distiller grains). These stresses occur within a potentially shifting and changing climate that increases the complexity of managing what are already complex animal systems. Animal production practices need to be developed that incorporate sustainability of their support system (feed supplies, etc.) and consideration of environmental variability.

But this context is only part of the challenge. The public has become increasingly concerned about how production and consumption of animal products affects human health, the environment, and animal welfare. Public concerns about issues such as antibiotic use, humane practices, and manure management and odor control in the livestock and poultry industries are increasing. Sometimes we lack the knowledge to respond to these concerns in an accurate and responsible manner. As we learn more about the genetic code of all living species, our understanding of the cell biology, biochemistry, physiology, and genetics of animals and humans will accelerate dramatically. The challenge for the future is to effectively utilize this information to advance animal biology in pursuit of more profitable and efficient animal management practices, to formulate new approaches to improve human health and fight disease, and to improve the interfaces between animal agriculture and landscapes (natural, managed, and urban).

New initiatives to characterize the genetic architecture and resources of various agriculture animals and aquaculture species are needed, including:

- Understanding gene networks that control economically important traits and enhancing breeding programs.
- Making genetic enhancements for growth, development, reproduction, nutritional value, disease resistance, stress resistance and tolerance, and meat quality and yields. Such enhancements require preservation of genetic diversity in livestock and related species.
- Enhancing **feed conversion efficiency** of livestock, poultry, and aquaculture.

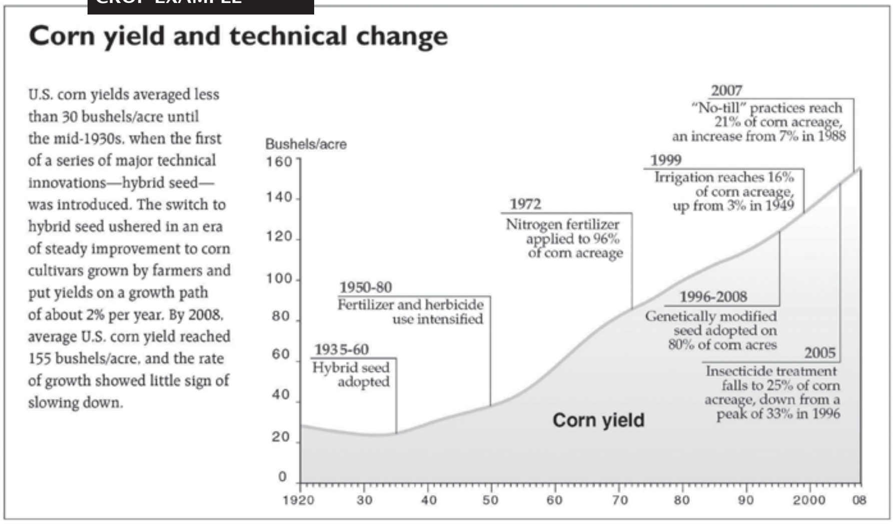
Our knowledge of animal biology is growing and will continue to grow with new advances in understanding. The key is to ensure that traditional and necessary disciplines and areas of study that are relevant to livestock industries (e.g., reproduction, genetics, and nutrition) grow not as discrete research activities but rather as integrated endeavors that consider mechanistic and holistic understandings of animals and their human consumers. These emerging areas of holistic exploration are the new priority areas that should underpin future animal agriculture. Thus, the challenge of animal agriculture becomes not how to remake or to redevelop its traditional aspects but how to integrate these aspects and their advances with the whole environment, of which humans are an integral part. Researchers then become true stewards of the environment by researching and managing their particular foci, including aspects of plant and animal agriculture, in ecological contexts.

DEVELOP NEW ANIMAL PRODUCTION TECHNOLOGIES, PRACTICES, PRODUCTS, AND USES

- Enhance animal productivity by maximizing their genome capacities and developing new animal breeds and stocks; by optimizing their relationship with the environment; and by adopting innovative management systems.
- Develop technologies for animal health, well-being, and welfare in all production systems to enhance nutrition, efficiency, quality, and productivity.
- Develop technologies and strategies to enhance energy and nutrition efficiencies in animal production systems.
- Develop technologies for animal waste utilization and management to reduce the impact of agricultural production on the environment.

Technological advances brought about by agricultural research and development have both improved yields and reduced input requirements. Public agricultural research investments are responsible for about half of the measured productivity gain in U.S. agriculture.

CROP EXAMPLE


Corn yield and technical change

U.S. corn yields averaged less than 30 bushels/acre until the mid-1930s, when the first of a series of major technical innovations—hybrid seed—was introduced. The switch to hybrid seed ushered in an era of steady improvement to corn cultivars grown by farmers and put yields on a growth path of about 2% per year. By 2008, average U.S. corn yield reached 155 bushels/acre, and the rate of growth showed little sign of slowing down.

Figure 3. (USDA-Economic Research Service)

IMPROVE THE ECONOMIC RETURN TO AGRICULTURAL PRODUCERS

While returns on previous public investments (e.g., in the form of high productivity growth of crops such as corn) have been nothing short of spectacular (Huffman and Evensen 2006) (Figure 3), these investments need to continue just to maintain yields at current levels (Alston et al. 2009). In addition, new investments in input-reducing and output-enhancing technologies are needed in emerging priority areas to maintain the nation's overall standard of living. These priority areas include a variety of crops such as fruits and vegetables, where technological innovations need to be complemented with research on new policies, markets, and distribution systems that deliver foods from diverse farms while balancing low costs to consumers and fair returns to farmers.

Social sciences research is shifting from an exclusive focus on individuals (farmers, consumers, entrepreneurs, intermediaries) to a science-based understanding of the roles, positions, and interactions of individuals within networks (Borgatti et al. 2009). This allows for a more comprehensive analysis and understanding of producer and consumer incentives, behaviors, and performance, and it has the potential to provide powerful insights into how best to spawn the innovation that will keep U.S. agriculture—and the U.S. economy more generally—at the frontiers of global competitiveness.

Even as the economy recovers, a continuation of current trends can be expected in terms of high obesity rates, with associated rising health care costs and the coexistence of hungry and food-insecure populations, unless systems to address these issues are employed. "**Food deserts**" will continue to spread across the nation, exacerbating the hunger-with-obesity problem among disadvantaged populations. Within the agricultural sector, a hollowing-out will continue, and rural areas will continue to experience economic and social decline.

Innovations in a number of areas are centrally important to future competitiveness and will eventually define how we provide a more healthy food supply to the citizens of this country. Important related questions come to the fore: Will expansion of local and regional food systems improve food security and sustainable production methods? Will the critical mass of farms needed to sustain viable agricultural input and output markets be retained? What is the tipping point in loss of farmland and farmers that could negatively impact various areas of the country, and what does this mean to the quality of life in this country? Infrastructure constitutes an important public good to the extent that it is part of sustainable food security for the United States. In light of all of these challenges, we need to

- Develop sustainable production systems that are profitable and productive and that include integration of crop and livestock production.
- Provide evidence-based recommendations for alternatives to the current price support system that will encourage diverse agricultural production.
- Explore the use of alternative economic models for stimulating farming, e.g., the use of innovative farmer support programs in addition to traditional price supports.
- Support the development of marketing infrastructure for crop bioproducts.
- Explicitly value ecosystem services provided by agriculture—and multi-functionality in general.

IMPROVE THE PRODUCTIVITY OF ORGANIC AND SUSTAINABLE AGRICULTURE

Many specific practices have been proposed as consistent with a sustainable approach to agriculture. However, given the generational time scales inherent in considering sustainability, the evaluation of the sustainability of food and agricultural systems may have more to do with an ability to evaluate complex systems and trade-offs than simply an ability to classify the system. In contrast, organic agriculture has been defined in terms of a specific set of practices that can be certified. The approaches and practices associated with organic production and food systems offer a number of options that agriculture may employ in facing the challenges of predicted global changes in climate and in the use of energy, water, and land. Therefore, the national agricultural science agenda needs to focus on the costs and benefits of organic production according to the holistic evaluation framework suggested above, and it needs to sponsor research that will help shape the future of organic agriculture as a changing, more resilient body of practices.

Organic agriculture provides a unique opportunity to invent systems that are sustainable in the face of currently predicted future constraints to production. These new systems can be more resilient in the face of future unpredictable challenges to agriculture and can address many of the needs described above. Organic systems deserve more attention in the national research agenda, because they are less reliant on fossil fuels than other systems (particularly due to elimination of synthetic nitrogen and pesticides) and because established organic systems can be as productive per unit of land area as more fossil-fuel-intensive systems. Specific concerns about organic systems—for example their reliance on cultivation for weed control, which leads to soil loss and higher energy costs—can be addressed through systems research and development. Furthermore, the historically holistic and systems orientation of the organic movement and organic farming (Stinner 2007) could help inform and facilitate the integration of more systemic approaches into research carried out to develop more sustainable agriculture in general.

IMPROVE AGRICULTURAL PRODUCTIVITY BY SUSTAINABLE MEANS, CONSIDERING CLIMATE, ENERGY, WATER, AND LAND USE CHALLENGES

- Improve efficiency and sustainability of agricultural production systems through systems-level evaluation that uses metrics such as energy (i.e., life cycle or **emergy**), human and social capital, ecosystem services, and human health outcomes, along with more standard economic measures.

  - Quantify and analyze the trade-offs of different policy options for different constituencies.
  - Develop collaborative researcher-stakeholder analyses of these trade-offs, and rapidly integrate scientific results with stakeholder/practitioner discoveries and local adaptations.
  - Explore agriculture's role in the transition from a continuous growth to a **steady state** economics model.
- Develop management strategies and tools that improve agricultural pest, weed, and disease control; soil building; and green manures and crop rotation; improve integrated animal-plant and other management strategies for sustainable production.
  - Ensure that agricultural production systems build and maintain soil structure and diverse biological communities both above and below ground.
  - Integrate animal and plant systems for efficient "closed-loop" **nutrient cycling**, with energy generation as an additional opportunity for managing nutrient cycles without waste or leakage.
  - Meet the challenge of providing sufficient nitrogen to maintain productivity while reducing or eliminating reliance on fossil fuels for the production of inorganic nitrogen.
  - Create plant and animal breeding programs that allow for coexistence and producer choice between decentralized resources and profit (e.g., Seed Savers) and centralized resources and profit (e.g., Monsanto); or create plant and animal breeding programs that address problems in the public domain that are not addressed by the for-profit sector (e.g., disease resistance in open-pollinated varieties that allow seed saving and sharing among resource-poor farmers).
  - Develop IPM that is independent of purchased inputs from centralized sources (i.e., that instead involves biologically- and ecologically-based methods).
  - Develop pest control inputs that are very selective and therefore not ecologically disruptive, that improve profitability for producers in both the short and long term, and that are accepted by society as being equitable and just in their costs and benefits.
  - Promote "parallel resistance," in which the agroecosystem stays ahead of the increasing rate of penetration by invasive species.
  - Encourage equipment development and adaptation through producer/user innovation and recycling, and encourage investment in large-scale and inexpensive production for equipment innovations.
- Examine the multifunctional costs and benefits of certified organic agriculture, including environmental conservation, production, health and nutrition, profitability, and energy efficiency.
  - Assess the trade-offs between organic and conventional agriculture using metrics such as energy (i.e., life cycle or emergy), human labor inputs, and human health outcomes.
  - Examine the optimal conservation, environmental, and production outcomes—including sustainability, nutrition content, profitability, and energy efficiency—for organically produced agricultural products.
  - Evaluate ecosystem service marketplaces and organic labeling as methods of returning value to producers for environmental benefits.

MAINTAIN A SUSTAINABLE ENVIRONMENT

- Develop efficient and sustainable farming and food processing systems that rely on renewable energy systems and decrease the carbon footprint, particularly those systems that convert agricultural wastes into **biomass** fuels that further improve the efficiency of a system's production.
- Develop environmentally friendly crop and livestock production systems that utilize sustainable feeding and IPM strategies.
- Develop methods to protect the environment both on and beyond the farm from any negative impacts of agriculture through optimum use of cropping systems, including agroforestry, **phytoremediation**, site-specific management, multicrop diversified farms, and perennial crops.

- Develop innovative technologies for reducing the impact of animal agriculture on the environment.
- Develop strategies, ecological and socioeconomic system models, and policy analyses to address conservation, biodiversity, ecological services, recycling, and land use policies.
- Develop agricultural systems that create fewer waste products.
- Create a clear understanding of the principles and facets underlying the concept of sustainability as it relates to urban and rural agriculture.

Expected Outcomes

Without the investments described above, agricultural systems that continue to have a narrow focus primarily on productivity will be highly vulnerable to increases in energy costs, loss of key fertilizer sources (e.g., phosphorus deposits), and climate variability. Even in the absence of these challenges, a "business-as-usual" approach to agriculture will continue to degrade soil and water resources and have adverse impacts on biodiversity, air quality, and other aspects of the environment. Agriculture will become increasingly unsustainable and will ultimately not be economically viable. Decisions about land use changes will be divorced from a societal appreciation of the importance of food production, and ultimately production capacity itself will be reduced as agricultural land is sold for development. Without development of data sets and holistic analytical tools with which to evaluate sustainability in agriculture, we will not be equipped to meet the enormous challenges anticipated in the near future. However, with investment in, and adaptation of, these new and universal approaches, agriculture will be subject to evaluation and assessment using the same set of tools and metrics and the same vocabulary as that used to evaluate energy use, carbon footprints, fair trade, etc., in a variety of land uses. Evaluating agriculture using a framework that places agricultural production, and ultimately stewardship, within this broader context will benefit farmers as well as consumers.

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2

Grand Challenge 2

We must adapt to and mitigate the impacts of climate change on food, feed, fiber, and fuel systems in the United States.

Framing the Issue

Climate change has become an even more daunting, more "grand" challenge since the last *Science Roadmap* analysis 10 years ago. Today, the evidence that climate change is already upon us is well documented, including substantial evidence that plants, animals, insects, and other living things are already responding. **Climate** models and their spatial resolutions have been improved, allowing regional climate projections at a smaller geographic scale and enabling an increased understanding of the earth's climate. While the climate is always changing, these models tell us that the pace of change within this century is likely to be faster by several orders of magnitude than the most recent ice age transition if society follows a "business-as-usual" scenario of fossil fuel-based emissions. In its *Fourth Assessment Report: Climate Change 2007*, the Intergovernmental Panel on Climate Change (IPCC, www.ipcc.ch), an international panel of leading climate scientists, concluded that there is a greater than 90 percent chance that rising globally-averaged temperatures are primarily due to human activities, and that by mid-century (2050), temperatures across most of the United States will likely increase by between 3 and 6°F, based primarily on a continuing increase in atmospheric greenhouse gases. There will also be changes in rainfall patterns and, potentially, increases in storm intensity resulting in higher risks of crop failures, natural disasters, and migration of affected populations.

Weather vs. Climate: What is the Difference?

Weather is the atmospheric condition (e.g., temperature, precipitation, humidity, wind) at any given time or place. In most places, weather is highly variable and can change from hour to hour, day to day, and season to season. In contrast, climate refers to long–term "weather averages." This can include the average frequency of extreme events, such as the average number of heat waves per year over several decades. The World Meteorological Organization considers the statistical mean and variability of factors such as temperature and precipitation over a period of 3 decades to evaluate climate trends, but climate can refer to other periods of time, sometimes thousands of years, depending on the purpose.

The impacts of climate change on agriculture, food systems, and **food security** will have socioeconomic, environmental, and human health implications. How can those involved in agriculture be prepared to take advantage of opportunities and minimize the risks and inequities of climate change impacts? What technologies, information, and decision-making tools are needed to guide our responses to help ensure sustainable agriculture systems? This challenge is different from those that agriculture and agricultural scientists have had to address in the past for several reasons, some of which are discussed briefly below.

Climate change is a global problem. The solution requires coordinated action by all people and all nations. Costs of mitigation and adaptive actions must be borne in the present but will have benefits in the distant future, making action politically difficult. The debate has become highly politicized, making it difficult for farmers, the public, and policymakers to sort through the information for decision-making purposes.

Decision making under uncertainty. The challenge of coordinated global action is made more difficult by the fact that, despite improvements in our models, there remains considerable uncertainty about some aspects of climate change, such as future emissions scenarios, precipitation patterns, and regional variation in the magnitude of change to expect this century. This uncertainty has fueled the public debate about whether there is really a threat and about what type of adaptation or mitigation cost today is warranted to avoid negative economic costs in the future.

Timescale issues in agricultural decisions and policies. Many decisions in agriculture are made on a short time scale in response to **weather** and weather extremes. The daily to seasonal time horizon commonly used by farmers for weather information is in sharp contrast to the time horizon of 50 to 100 years or longer discussed in most climate change literature. However, many important decisions that farmers make do consider a longer (i.e., decades-long) time horizon, such as investing in an irrigation or **tile drainage** system; new livestock facilities or renovations; purchasing or selling land; and planting tree crops and forests. Some policy decisions relevant to agriculture, such as taxpayer investment in large-scale water management projects or investment in research, will operate on longer time horizons. Furthermore, many research efforts that might address adaptation to climate change require longer-term projects on the order of a decade or two.

Complexity and interconnectedness of supply chains. Chains of production, distribution, and marketing of agricultural products are highly complex. The actors associated with each of these links in the chain make decisions based on unique types of data and have their own sensitivities to climate change and climate change policy. Changes in climate may result in a need to transform entire chains of production and marketing systems.

Nonclimate factors affecting agriculture and adaptive capacity. Climate is not the only change that agriculture is faced with. Population growth, land use change, energy cost, and demand for biofuels collectively will lead to transformations in agriculture in some regions.

Pressures for mitigation as well as adaptation. Concern about climate change places pressure on all industries, including agriculture, to engage in mitigation efforts. There are many opportunities for agriculture to contribute to a goal of reducing greenhouse gas emissions and **sequestering carbon**.

Rationale and Justification

EVIDENCE OF CLIMATE CHANGE

Evidence of climate change relevant to agriculture is already apparent across most of the United States. In addition to increases in air and water temperatures, observations have shown a reduction in the number of frost days, increased frequency and intensity of heavy rainfall events, rising sea levels, and reduced snow cover. Since the 1970s, temperatures across the United States have risen faster in winter, particularly in the Midwest and High Plains, where winter temperatures average more than 7°F warmer than they did three decades ago. Similarly, climate projections indicate that increasing winter precipitation will be offset by small increases or decreases in summer rainfall. Changes in other hydrologic parameters, such as glaciation, stream flow, and snowmelt, have also been documented and are already affecting water availability for agriculture, particularly in the West.

In addition to physical evidence of climate change, there is substantial evidence that the living world is responding to recent climate change. The peer-reviewed literature is filled with well-documented examples of earlier spring bloom dates for woody perennials, earlier spring arrival of migratory insects and birds, and range shifts to higher latitude and elevation for many insect, plant, and animal species. Some aggressive invasive species, such as the notorious Southern weed kudzu, are projected to benefit by future climate change and to spread their range northward.

These trends are likely to continue throughout this century—regardless of the future emissions of greenhouse gases—due to the inertia of the climate system (e.g., inertia associated with factors such as warmer oceans and the longevity of carbon dioxide emissions in the atmosphere). If greenhouse gas emissions continue in a "business-as-usual" trend, average annual temperatures are expected to increase by as much as 10°F by 2100, particularly across the central parts of the United States. As mentioned above, by mid-century, temperatures across most of the United States will increase by between 3 and 6°F. Again, to put these projections in perspective, they represent a pace of warming that is about 100 times greater than the pace during the most recent ice age transition. There are also important regional differences in climate change across the United States that must be understood in order to develop region-specific societal response options.

IMPACTS OF CLIMATE CHANGE

Assessments of climate change impacts on U.S. agriculture by the U.S. Climate Change Science Program (**www.sap43.ucar.edu**), as well as numerous regional analyses, have identified a number of key climate-related impacts. Some of these are described briefly below:

- *Increasing carbon dioxide* levels can stimulate plant growth and yield, particularly of plants with the C_3 photosynthetic pathway (a pathway for carbon fixation in photosynthesis), but the magnitude of response varies greatly among species and can become negligible under high temperature stress or nutrient deficiency. Many aggressive, fast-growing C_3 weeds benefit more than crop plants from rising carbon dioxde and become resistant to control by glyphosate, the most commonly used herbicide.
- *Warmer summers and longer growing seasons* could provide opportunities to obtain higher yields and/or to explore markets for new crops, especially in high latitude regions. Negative impacts will include: increased seasonal water and nutrient needs; more generations per season of some insect pests; and a longer growing season for weeds.
- *Increased frequency of summer heat stress* will have negative effects on the productivity or quality of many crop species. In addition, heat stress has negative effects on productivity and survival of livestock and reduces milk production by dairy cows.
- *Warmer winters* will expand the winter survival and range of many weed, insect, and disease pests. Winter "chilling requirements" of perennial fruit and nut crops may no longer be met in some warmer growing regions, reducing productivity, while historically cooler regions may be able to grow new fruit or nut crop varieties or new winter cover crops that were previously restricted by cold temperatures.
- *Increased frequency of heavy rainfall events* can have direct negative effects on crop root health and yield. They also delay planting, harvesting, and other farm operations; increase soil compaction; wash off applied chemicals; and increase runoff, erosion, and leaching losses.
- *Increased frequency of summer drought* will bring more frequent drought-related yield or quality losses due to the increased crop water requirements that will occur with warmer summer temperatures, lower summer rainfall, or both.
- *Most western high-value agriculture depends on irrigation provided by snowmelt*, so as winter and spring temperatures warm, less water will be available from this source, increasing the tension between agricultural and municipal uses of water.
- *Frequency of extreme weather events and seasonal variability* have a major impact on agriculture but remain difficult for climate modelers to predict. For example, winter temperature variability can cause **de-hardening** or premature leaf-out and flowering of perennial plants, increasing the risk of freeze or frost damage despite overall warming trends.

Given a number of potential climate-related impacts, U.S. agriculture will not continue "business as usual."

Current Capacity and Science Gaps

- Building adaptive capacity for agriculture will require addressing uncertainties in climate model projections regarding precipitation, frequency of extreme events, and temporal and spatial climate variability.
- Farmers need better decision tools for determining the optimum timing and magnitude of investments for strategic adaptation to climate change. We need to engage the agricultural community more completely in research programs that lead to agricultural technologies, practices, and policies for increasing resilience and adaptive capacity. Such capacity will not only lessen the impacts of climate change on agriculture but will also provide improved strategies for dealing with year-to-year natural climate

variations. New social science research needs to be integrated into research on agricultural practices and policies to help overcome some of the barriers to progress in this area.

- Research on how farmers and other decision- and policymakers should respond to weather variability and climate change needs to consider the wide range of planning horizons. Advances coming out of the decision sciences on topics such as risk perception, **temporal discounting,** decision making under uncertainty, participatory processes, decision architecture, equity, and framing have not been taken into account in the design of effective adaptive agricultural management mechanisms or programs designed to influence behavior to reduce greenhouse gas production. These cognitive and cultural factors have a major influence on the communication of, understanding of, and response to, scientific information.
- A transdisciplinary, systems approach is needed for both technological adaptation and policy design that takes into account all of the components of agricultural systems, from the farm to the market and the consumer. In addition, socio-economic and social equity issues will need to be addressed in agricultural areas that may need to be transformed from one agricultural system to another agricultural system—or even to another livelihood system.
- The new opportunities and challenges for agriculture that climate change poses will require new research partnerships with urban and regional developers, environmental agencies, and nongovernmental organizations.
- To improve mitigation efforts in the agriculture and food industry sectors we need better tools for monitoring, accounting for, and applying value to greenhouse gas emissions reductions and soil **carbon sequestration**. Mitigation will bring benefits and costs to farmers, and research is needed to understand policy options that will help achieve benefits for agriculture and society.

Research Needs and Priorities

CLIMATE SCIENCE

Although significant strides in climate modeling have been made over the last decade, model projections continue to have inherent uncertainties. Both physical and empirical modeling work is required to bridge the gap between the coarse resolution of climate model output and the spatial and temporal scale requirements for agricultural decision making. Work is needed to directly link agriculture models that simulate processes such as soil nutrient levels, yield, and disease with climate model output, recent and historical climate observations, and weather forecasts. Specific research priorities include:

- Development of climate change scenarios relevant at local to regional scales and time horizons. These might include factors ranging from unique physical features not captured by climate models, such as lake influences, to regional projections of changes in land use, environmental policies, or economics.
- Improvement and development of physical and empirical downscaling techniques tailored to agriculturally relevant variables. Examples of these variables may include leaf wetness, livestock heat stress, and drought and freeze risk. Many current methods are too simplistic in their assumption of constant (current-day) variance of these phenomena.
- Work on methods to spatially interpolate climate data. Validation of gridded downscaled climate model data as well as tuning of empirical downscaling techniques will benefit from gridded observed data, as the stations themselves do not represent elevation or coastal influences adequately. Such gridded climate datasets will also facilitate monitoring efforts and the development of climate-based decision tools.
- Development of sophisticated real-time weather-based systems for monitoring and forecasting stress periods, pest and weed pressure, and extreme events. Current guidelines for many agricultural practices are based on outdated

observations and the assumption of a stationary climate.

CROP, LIVESTOCK, WEED, AND PEST MODELS

Improve and evaluate existing models for their use in climate change and weather variability studies; for addressing carbon, nitrogen, and water changes in response to climate; and for assessing resource needs and efficiencies. In addition:

- Develop and test new crop models beyond those currently available, including those for perennial fruit crops, vegetables, and other "specialty" food crops; wood products; and biofuel crops.
- Develop and test new livestock models focused on heat stress and greenhouse gas mitigation in livestock facilities.
- Develop and test new insect, pathogen, and weed models to project future range shifts, population dynamics, and epidemiology.

IMPROVED ECONOMIC ASSESSMENTS OF CLIMATE CHANGE IMPACTS AND ADAPTATION

Economic assessments based on higher-resolution climate and economic data are needed to provide more accurate estimates of climate change impacts, the potential costs and benefits of adaptation, and to validate and calibrate models.

- Quantify costs and benefits of adaptation at the farm level and for specialty crops and livestock as well as grain crop production systems.
- Assess economic impacts and costs of adaptation beyond the farm gate for entire foods systems.
- Integrate economic with environmental and social impacts of climate change and adaptation. Examples include valuation of **ecosystem services,** impacts on farm structure and rural livelihoods, and equity and social justice issues.

DECISION SCIENCE

Incorporate advances in decision sciences that could improve uncertainty communication and the design of mitigation and adaptation strategies.

- Risk perception, investment decision making under uncertainty, and the role of temporal discounting.
- The role of participatory processes in scenario development.
- Extensive testing and design of decision support tools for adaptation and mitigation measures appropriate for different producers and consumers.

CONCEPTUALIZING AND MODELING COMPLEX SYSTEMS

Transdisciplinary approaches are needed to achieve models that encompass the complexity of food systems, including interactions across spatial and temporal dimensions, climate and economic thresholds, and adaptive capacity.

- Characterizing and analyzing climate uncertainty and how it impacts: system productivity; demand for water, nutrients, and other resources; and the environment.
- Spatial and temporal dynamics of production systems.
- Systems characterization, including a comprehensive coverage of farm sizes and types, commodity transportation and storage systems, and food processing and distribution.

ADAPTIVE STRATEGIES AND MANAGEMENT

Integration of models into adaptive management at farm and food system scales is needed. Research should identify where investments in adaptive capacity will be most beneficial for both crop and livestock systems and for systems beyond the farm gate.

- Develop adaptive strategies for livestock, including managing weather extremes; taking into account costs of and constraints to renovation or relocation of facilities; information on breeds more tolerant to new stresses; managing waste; and biofuel production.
- Develop new, more tolerant crop varieties through conventional breeding, molecular-assisted breeding, and genetic engineering. University emphasis should be on specialty crops and other categories not currently being addressed by commercial seed companies.
- Develop new, rapid breeding technologies that can be used to quickly respond to emergent vulnerabilities as microclimates become suitable for previously nonthreatening diseases and pests.

- Develop improved water management systems and irrigation scheduling technology.
- Develop adaptive strategies for weed and pest control, such as improving regional monitoring and IPM communication regarding weed and pest range shifts and migratory arrivals; enhancing real-time weather-based systems for weed and pest control; developing nonchemical options for new pests; and developing rapid-response action plans to control invasive species.
- Develop adaptive strategies for storage and transport systems, such as redesign and relocation of infrastructure, and assess impacts of rises in sea levels on port facilities.
- Develop adaptive strategies for food processing and marketing systems.

GREENHOUSE GAS MITIGATION AND SOIL CARBON SEQUESTRATION AND MONITORING

Further research is needed to establish the science base needed to implement greenhouse gas mitigation policies.
- Systems and best management practices to reduce greenhouse gas emissions for crops, animals and animal waste systems, and food processing and other food system activities beyond the farm gate.
- Systems and practices to offset emissions by sequestering carbon in trees and soil and also methods to quantify offsets, taking into account measurement uncertainty.
- Greenhouse gas and carbon accounting tools for farmers and food system users.
- Policy mechanism design for greenhouse gas mitigation.

COMMUNICATION

Cognitive and cultural factors have a major influence on how scientific information and scientific uncertainty are communicated, understood, and responded to by various stakeholder groups. Research goals to be addressed include:
- Identification of gaps in knowledge, socioeconomic biases, and other factors constraining effective communication to various target audiences.
- Evaluation of framing of issues for optimum communication effectiveness for various target audiences.
- Use of new technologies and social networking tools for communication to selected target audiences.

POLICY ANALYSIS

There is a need for research to identify appropriate policies to facilitate both mitigation and adaptation and to understand how these policies interact with each other and with other policies.
- Economic impacts of mitigation policies on agriculture and the food sector, including impacts on costs of energy and other inputs, environmental impacts, and regional and social equity.
- Evaluation of various policy mechanisms, including tax incentives, environmental and land use regulation, agricultural subsidy and trade policies, insurance policies and disaster assistance, soil and water conservation policies, and energy policies including those involving carbon trading and biofuel production.

Expected Outcomes

Because of the extreme importance of this challenge and the complications associated with it, sustained major investments are needed in research to develop the new technologies, policy options, and information to transform agriculture into an industry that is more resilient and adaptive to weather variability and climate change. Private decision makers need information that can reduce uncertainty about climate change and its impacts in the systems they are managing now and in the future. Public decision makers need information that can show the economic and other public benefits of policies that are needed to reduce greenhouse gas emissions and facilitate adaptation.

With timely and appropriate proactive investment in research as recommended in this Grand Challenge area, the agriculture and food systems sector of the U.S. economy will have the necessary tools for strategic adaptation to meet the challenges and take advantage of any opportunities associated with climate change. Policymakers will have information to facilitate adaptation and also minimize inequities in impacts and costs of adaptation. Farmers and others in the food industry will also contribute significantly to greenhouse gas mitigation by having access to new tools and incentives for mitigation, including new greenhouse gas and soil carbon accounting tools.

3

Grand Challenge 3

We must support energy security and the development of the bioeconomy from renewable natural resources in the United States.

Although renewable energy can be supplied from many sources, including solar, tidal, hydroelectric, and wind sources, it is **biomass** that offers the greatest growth potential as part of our national renewable energy portfolio. The vast majority of biomass in the United States comes from the land, although smaller amounts could eventually be supplied by algae. It follows, then, that any direct or indirect diversion of primary plant productivity into biofuels and other forms of energy will have broad ramifications for food and fiber and the underlying agricultural system.

Appropriate research investments made today can ensure the vibrancy, resiliency, and profitability of our agricultural system in the face of society's increasing demands for renewable energy. Such investments can also secure new economic opportunities for agriculture in a future that extracts not just energy but also fabrics, **polymers**, and other valuable chemicals in the form of renewable bioproducts from agricultural materials. But we must act now if we want to maximize the benefits of the nation's interest in renewable fuels.

Goal: Devise agricultural systems that utilize inputs efficiently and create fewer waste products.

RESEARCH NEEDS AND PRIORITIES

There is a pressing need to develop new linkages in agricultural energy and **nutrient cycles**, both among individual farms and at a regional scale. The abundant energy in agricultural wastes and residues can fuel not just the agricultural sector but also other industrial processes for mutual benefit. For example, the energy efficiency of anaerobic digestion is more than doubled if there is demand for both electricity and heat. Successful collocations of greenhouses or ethanol facilities with manure digesters have provided proven examples of the synergies that can result from such integration.

But there are many other residue recycling possibilities that will require innovative strategies and new business models if they are to become successful realities. New technologies must be developed to process crop residues and wastes into fertilizer products that are easy to transport and predictable to use. The markets for such products will redistribute nutrients from farms with excess residues to those with fertilizer demand, improving air and water quality while simultaneously cutting fossil energy demand.

There are tremendous energy and nutrient resources in food and food processing wastes; in other organic residues from the landscape, construction, and recycling industries; and in municipalities. Each of these sources has its own unique characteristics, so a diverse range of approaches will be required. Some of these materials may prove to be highly attractive **feedstocks** for biofuels, but even after the fuel is produced, large volumes of residues will remain. Some residues will best be recycled as nutrients and organic matter on agricultural land, while others can be manufactured into value-added products or used to meet **process-heating** requirements. Developing new biochemicals and biomaterials from these residues will challenge the imaginations of new generations of scientists, engineers, and entrepreneurs in the decades to come.

EXPECTED OUTCOMES

- Production of renewable energy from agricultural feedstocks.
- Increased farm income from energy and **coproducts**.
- Reduced dependence on fossil fuels and fertilizers.
- Less nutrient loss and enhanced water quality.
- Reduced landfill costs for the landscape, food, and fiber industries.
- New biofuel, biochemical, and biomaterial products and markets.
- Increased income and quality of life in both rural and urban communities.

The impacts of an expanded, agriculturally-based biomass feedstocks industry will not end at the farm gate.

Goal: Assess the environmental, sociological, and economic impacts of the production of biofuels and coproducts at local and regional levels to ensure sustainability.

RESEARCH NEEDS AND PRIORITIES

USDA and the Department of Energy estimate that by 2030 the mass of biomass feedstocks available for bioenergy may be greater than a billion tons per year. To put this in perspective, the current U.S. food system relies on a little less than a billion tons of agricultural inputs a year. Such a doubling of agricultural productivity will rely in large part on more intensive farming systems, including advances in crop genetics, production practices, and technologies. The challenge will be to achieve this intensification while enhancing the healthy environment, profitable farms, and stable rural communities that society expects agriculture to provide.

The development of the domestic biofuels industry has benefited from strong governmental and consumer support, predicated on expectations that this industry will meet or exceed various sustainability goals. Foremost among the environmental sustainability criteria have been the criteria for greenhouse gas emissions, which are now being codified as low carbon fuel standards and compared against diesel and gasoline as benchmarks. But because agricultural greenhouse gas emissions are closely coupled with fertilizer use (nitrous oxide) and tillage (carbon dioxide), there can be large variations in the carbon footprint of any particular crop depending on how it was grown.

Current regulations do not address this variation, and thus they miss opportunities to use market forces to motivate more sustainable agricultural practices. Many of those more sustainable practices would also reduce nutrient losses and increase **carbon sequestration**, two impacts that are already monetized through nutrient trading and carbon markets in some states. Over time, markets may emerge for other **ecosystem services**, such as for soil erosion, soil quality, and biodiversity.

Documenting and pricing these payments for environmental services could provide strong incentives for farmers to meet a range of sustainability goals. However, the impacts of specific agricultural practices and cropping systems on these phenomena have not received sufficient research attention in the past. Accurate and credible assessments of these environmental impacts will require significant investments in multidisciplinary agroecosystem research, as well as the development of farming system models and decision aids to minimize the need for detailed measurements on every farm.

While a combination of sales of biomass feedstocks and payments for ecosystem services may appear sufficient to provide profitable income from energy crops, there are other factors that go into the socioeconomic sustainability of a farm. Risk management will be an issue for crops that do not currently benefit from subsidy or insurance programs. For perennial crop systems, financing will be required for several years before a new planting will become profitable. Seasonal labor availability, management requirements, and market stability also must be addressed. Identifying and addressing the motivations and concerns of producers will be critical to increasing the biomass feedstocks supply.

The impacts of this new industry will not end at the farm gate. **Life cycle analysis** of biofuels and bioproducts stretches from "cradle to grave" and must include significant effects along the entire value chain. We need a nationally-recognized method for quantifying the entire life cycle analysis as well as development of the data that will drive the quantification model. Presently, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is accepted by federal agencies, but it has gaping holes in the area of modeling of cropping systems and in some other areas.

On the economic side, farm profits will help undergird local communities as well as regional commercial centers. Businesses up and down the value chain will need support to provide inputs, transport and logistics, and coproduct manufacturing. Community-scale impacts will include those affecting health care and social services, workforce training, and housing. Understanding these impacts will require new methods of analysis by sociologists, economists, scientists, and engineers, all contributing to the integrated assessment, evaluation, and ultimately improvement of the agricultural systems on which a biobased economy will increasingly depend.

EXPECTED OUTCOMES

- Improved environmental outcomes from biomass production systems.
- Increased farm profitability through payments for ecosystem services.
- More stable farm income due to use of farm planning and risk management tools.
- Reduced dependence on imported fuels.
- More efficient supply chains and conversion processes.
- Better social service planning and environmental planning in rural communities.

Goal: Develop technologies to improve production–processing efficiency of regionally appropriate biomass into bioproducts (including biofuels).

RESEARCH NEEDS AND PRIORITIES

In addition to providing for the increasing needs of a growing world population, we must provide renewable energy, **biopolymers,** chemicals, and more, all in an efficient, environmentally-sustainable, and economically feasible manner. Production of biofuels from food crops is a valuable first step, but the future will inevitably involve solutions that utilize either nonedible portions of these crops or sources that are wholly dedicated to biomass production.

The nature and composition of the biomass feedstock is highly dependent on local and regional conditions. Also, biomass, unlike petroleum, is of lower density and is distributed over larger regions. Both of these realities need to be considered in developing solutions that take into account technical, economic, and environmental considerations.

Variability within a biomass species—as well as the fact that multiple species will be grown within the same geographic area due to a number of productivity, environmental, and other factors—stipulates that future solutions ought to address sustainable conversion of mixed biomass feedstocks. Much of the focus thus far has been on single crops. Future solutions ought to be adaptive and robust, including the development of novel methods of conversion suitable for use in a simple, single-pot approach for the simultaneous conversion of mixed biomass species.

The technology thus developed should be able to handle the diverse physical and chemical characteristics of various biomass species as well as lead to effective conversion in the presence of various side products, e.g., fermentation inhibitors, **lignin**, etc. Thus, the objective ought to be to integrate multiple crops and other sources of biomass, including mixtures, into the conversion scheme, building several novel processing approaches around these real-world feedstocks, and potentially targeting unharnessed synergies.

Both the agriculture and forest industries are mature, with substantial existing infrastructure. Next-generation biomass conversion solutions must utilize the existing infrastructure fully, leveraging what already exists. In addition to the production of biofuels and bioenergy, sufficient focus must be placed on developing multiple products in an integrated fashion. Renewed emphasis thus must be placed on lignin and its effective utilization as a renewable feedstock for polymers, chemicals, and value-added coproducts.

Any future technologies should include a simultaneous, more thorough and comprehensive environmental sustainability analysis in addition to technical and economic feasibility considerations. For a sustainable **bioeconomy**, ecosystem services contributing to water, air, and soil quality should be factored into the overall products and services derived from the landscape, in addition to the varied bioproducts described earlier.

EXPECTED OUTCOMES

- Optimal benefits for rural communities as they create and grow renewable fuels businesses.
- Increased income and quality of life in rural communities.
- Tailored opportunities for a variety of local agricultural regions to extract value from renewable fuels.
- Application of new, cutting-edge technologies to land-based systems.

Goal: Expand biofuel research with respect to non-arable land, algae, pest issues that limit biofuel crop yields, and emissions of alternative fuels.

RESEARCH NEEDS AND PRIORITIES

Cultivation of dedicated energy crops on lands that are less suitable for food and feed crops offers several advantages, particularly if this can be done with few inputs and in such a way that greenhouse gas emissions are minimized. Yet even when grown on marginal land with low inputs, these bioenergy crops must continue to improve in both overall yield and in their ease of conversion to biofuels. This is a particularly complex problem given that regional variations in soils and **climate** are large and that there are a number of potential bioenergy crops, along with algae, that can be considered.

This complexity mandates an integrated systems approach that includes, for example, strategic placement of perennials along streams and on steep slopes, but that also encourages the ecological restoration of marginal, abandoned, and **brownfield landscapes** for productive use. Developing these strategies will require a substantial increase in funding for research to address the numerous questions that have yet to be answered. Research is needed, for example, on the plant biotechnology of crop stress tolerance and fertilizer use efficiency, on commercial-scale agronomic and engineering practices, on economic policies, and on community desires.

Although production of biofuel crops on non-arable lands has promise, there are consequences of land-use changes that must be examined. Models must be developed to assess—based on a range of environmental and socio-economic criteria—the suitability of such land-use changes for biofuel production. These models must be verified, validated, and then translated into user-friendly online tools to help farmers and communities make the decisions that are right for them. Certain biofuel crops grown on non-arable lands can actually improve biodiversity and increase natural habitats, but these benefits may be negated if these energy crops are grown as monocultures instead of polycultures. Likewise, the timing of harvests could substantially affect these new wildlife habitats.

By definition, these lands are deemed poor or marginal for farming because they possess one or more major limitations for crop growth, e.g., poor soil fertility, a lack of water, extreme temperatures, or inadequate sunlight. Consequently, proper management of these lands is necessary for biofuel crop productivity, and this may also result in benefits related to soil carbon fixation. Investigations into fertilizer applications, irrigation, tillage, and other agronomic practices must be conducted to reach these goals.

In addition to instituting best management practices to maximize yields while minimizing inputs, genetic improvement of regionally-appropriate biofuel crops is critical. Unlike traditional crops that have been domesticated and bred for many thousands of years, biofuel crops have not been as intensively selected and studied. Classical breeding, along with genomics and biotechnology research, must be focused on the improvement of biofuel crops for characteristics that suit sustainable production systems. These characteristics include tolerance to drought, to saline conditions, to pests and pathogens (particularly if monocultures are employed), and to cold. To increase biomass production and use efficiency, these crops should also be genetically improved for faster growth, improved photosynthesis and nitrogen metabolism, altered patterns of nitrogen distribution between aboveground and belowground organs, and quality traits such as more fermentable carbohydrates or higher oil content.

Although, a number of studies have shown that producing and using biofuels results in lower greenhouse gas emissions than production and use of petroleum fuels, there are many unanswered questions regarding such emissions over the life cycle of a particular biofuel crop. Consequently, detailed life cycle analyses must be undertaken.

Algae can also be used as a biofuel feedstock for both oil and cellulose production. Advantages of algae are that they require less land, that they can be grown on non-arable lands or water bodies that are inadequate for farming, and that their biomass can be produced all year. The amount of oil that can be produced is dependent upon essential factors such as sunlight and carbon dioxide levels. Algae have not been investigated as extensively as other biofuel crops. Cost projections are presently high, and industrial development seems likely to depend on government financial support and the ready availability of sunlight, nutrients, and especially water. Consequently, more research is needed in the areas of land-use options, **photobioreactor** efficiency, heat and mass transfer in both contained and open systems, genetic modifications for improved biofuel feedstock characteristics such as increased growth rates and oil content, and temperature tolerance, along with life cycle analyses that are comparable to those employed for bioenergy crops.

EXPECTED OUTCOMES

- Reduced dependence on fossil fuels.
- Increased use of once nonproductive lands.
- Environmentally sustainable bioenergy systems.
- Reduced production of undesirable emissions.
- Better understanding of mechanisms controlling and influencing plant growth.

Goal: Restructure economic and policy incentives for growth of the next-generation domestic biofuels industry.

RESEARCH NEEDS AND PRIORITIES

The corn ethanol industry has now matured to the extent that it has almost enough capacity to meet the 15 billion gallon portion of the **Renewable Fuel Standard** that is indexed to corn-based ethanol. The most likely scenario for the future is that corn ethanol production capacity will stay around this level. The big question is what happens with **cellulosic** and other advanced biofuels. Thus, one priority for policy is that it should be oriented toward advancing the inclusion of these other fuels as part of the domestic renewable fuels mix.

A move toward cellulosic biofuels can address two public concerns that constrain future domestic biofuels growth: perceived conflicts with environmental goals and perceived conflicts with food production goals. Environmental concerns about net energy production and greenhouse gas emissions have long been part of the corn ethanol debate. Low-carbon fuel regulations developed by the California Air Resources

Board and the U. S. Environmental Protection Agency address energy and greenhouse gas concerns through life cycle accounting. By considering indirect land-use effects, regulations may also defuse the food versus fuel debate by encouraging cellulosic feedstock production on abandoned and marginal land. Other sustainability concerns, including soil and water quality, biodiversity, and socioeconomic impacts, have yet to be addressed within the U.S. regulatory structure, but they are part of international sustainable biofuels certification programs. Forward-looking policies and incentives are needed to ensure that U.S. cellulosic feedstock production practices will satisfy evolving domestic and international expectations.

Policy can also have significant impacts on the types of biofuels produced from cellulosic feedstocks. Further growth of ethanol is limited by a current "blend wall" of 10 percent, with most ethanol in the United States consumed as "E10" (that is, fuel that is 10 percent ethanol by volume). "E85" (fuel that is 70 to 85 percent ethanol by volume) constitutes a tiny fraction of total consumption and is unlikely to grow very fast, as it can be used only by so-called **"flex-fuel" vehicles**, of which there are a limited number in the existing U.S. fleet of vehicles. The blend wall arises because we have reached a national consumption level that meets or exceeds what can be marketed as "E10." We consume about 140 billion gallons of gasoline in the United States annually. Even if we could blend every drop of that with 10 percent ethanol, the ultimate maximum would be only 14 billion gallons of ethanol. However, we cannot blend every drop. Most industry experts argue that around 9 percent is the effective maximum that is achievable.

This means the blend wall is reached at about 12.6 billion gallons of ethanol, which is less than the current 13 billion gallons of ethanol production capacity. One reason that more than a billion gallons of that capacity is not operating is that there is no place in the market to put the ethanol. The ethanol glut relative to the blend wall means that ethanol today is priced on a break-even basis with corn instead of being linked to crude oil as it was previously.

The blend wall also affects cellulosic biofuels. Since corn ethanol already fills the blend wall limit, there is no room in the market for cellulosic ethanol. For the biochemical process for cellulosic feedstocks, ethanol is the main end product. But since there is no market for additional ethanol at the current blend limit, any progress in advancing that technology depends on first expanding the blend limit.

Challenges to increased biofuel use can also be addressed through the development of "drop-in" biofuels, i.e., biofuels that are compatible with existing vehicles and infrastructure. **Thermochemical biomass technologies** can produce hydrocarbon fuels directly, and they can also produce **pyrolysis oils** that can be converted into bio-based gasoline, diesel, and jet fuels using conventional petroleum refining technologies. And, fermentation processes can produce butanol and hydrocarbons from genetically modified microorganisms.

While technical solutions to these challenges are increasingly available, the investments necessary to implement them are severely hampered by risk and uncertainty. There are three major sources of uncertainty in biofuels investments: market uncertainty, technology uncertainty, and government policy uncertainty. Oil prices need to be around $120 per barrel (42 U.S. gallons) for most of the cellulose technologies to be viable without subsidies, so oil price uncertainty is a considerable factor in the uncertainty in biofuels investments. And even though tremendous advances have occurred in the technologies, there is a pressing need for commercial processing plants to address technology risk at scale. Finally, both the corn and cellulose biofuel subsidies are subject to future legislative decisions. The impact of the Renewable Fuel Standard is not certain, as it contains many opportunities to adjust the standard downward. Lack of consensus about the impacts of biofuels on food and the environment puts these supportive government policies at continued risk. The biggest task for government policy makers who want to see the cellulosic biofuels industry grow is designing policies that effectively deal with these uncertainties.

EXPECTED OUTCOMES

- Cellulosic ethanol technologies take root and provide economic opportunities for rural communities.
- These fuel and feedstock production practices minimize greenhouse gas emissions and maximize other environmental benefits.
- Advances in technologies produce butanol, biogasoline, and non-ester biodiesel that “drop in” to existing fuel distribution systems and vehicles.
- University policy analysts provide input to new government policy for advancing biofuels that contribute to energy independence from foreign oil.
- The food versus fuel debate is avoided.

4

Grand Challenge 4

We must play a global leadership role to ensure a safe, secure, and abundant food supply for the United States and the world.

> “. . .*in the next 50 years we are going to have to produce more food than we have in the last 10,000 years, and that is a daunting task*.” —Norman Borlaug, Nobel Laureate

Framing the Issue

The world population—6.9 billion people at the time of this writing—has a net gain of one person every 13 seconds. During the past decade the population increased by 685 million people. A billion people are undernourished—more than at any other time in recent history (Food and Agriculture Organization 2009). The world's food supply depends upon a complex and multifaceted system of producing, harvesting, storage, processing, distributing, marketing, and consuming. Rapid increases in the world's population will challenge the sustainability of natural resources and necessitate concomitant increases in food production, nutritional quality, and distribution efficiencies. Advances in science and technology are essential to assure a safe, secure, and **abundant food supply**.

Impacts of technology. Technology can be a driving force for increased productivity. Recent technological innovations have resulted in improved yields and enhanced resistance to pests and environmental conditions, bolstered nutritional and esthetic quality, reduced need for chemical fertilizers and pesticides, and lowered farmer input costs (CAST 2010).

Environmental degradation. The world is facing an alarming new level of environmental degradation characterized by rapid **climate** change; increased frequency of extreme **weather** patterns; reduced quantity and quality of freshwater resources; and diminishing arable land area due to industrialization, urbanization, and alternative uses of land. All of these elements have significant implications for resource sustainability, water availability, and **food security** (Kirschenmann 2007).

Shortage of agricultural labor forces. One percent of the U.S. population is directly involved in food production. As many farmers and ranchers diversify their income sources or migrate to urban areas to seek a more financially secure life, the resulting shortage in farm labor affects economic, social, and managerial decisions in the agricultural sector.

Impact of global commerce. Commercial agriculture and global trade will continue to be of primary importance in ensuring an adequate global food supply. In the United States, although 13 percent of foods are imported, recent trends for buying locally-produced and organic foods will probably continue or increase. On the other hand, although small family-owned farms continue to supply much of the food in developing countries, they, too, are becoming more reliant upon imported foods. To ensure a safe, secure, and abundant food supply for all nations as foods are distributed around the globe, new approaches and standards are needed for the assessment of **food safety** risks and the maintenance or enhancement of nutritional quality.

Global terrorism. Given that contamination of foods with human pathogens or toxic chemicals can have disastrous impacts, there is a risk of intentional tampering with the food supply—at multiple points from farm to fork—by those with harmful intent (Monke 2007). Other threats for terrorism arise as hungry people struggle to survive in times of global financial and food crises, climate change, and devastating natural disasters (Ban-Ki Moon 2009).

Global food safety. Although the United States enjoys one of the safest, most secure, and most abundant food supplies in the world, health-related costs from foodborne illness in the United States remain high. The Centers for Disease Control (CDC) estimated that food contaminated with pathogens and toxins causes 76 million illnesses and 5,000 deaths annually in the United States (Mead et al. 1999). The burden of foodborne illness on the U.S. economy is $152 billion per year (Scharff 2010), not including additional economic impacts on business and markets. Research is needed to develop innovative technologies that are both effective and affordable. Global food safety concerns are underscored by the growing global food trade and the lack of regulation, enforcement, and resources in many countries. The difficulties encountered in assessing, tracking, and eliminating foodborne hazards from domestic sources are amplified globally. Therefore, establishing global food safety standards and building collaborative international intellectual resources are critically important.

Lack of scientific backing for effective regulatory policies. Recent increases in the incidence and impact of foodborne illnesses and contaminants led Congress and federal agencies to reexamine regulatory policies. Although the need for new and more effective regulations is clear, our understanding of the nature and causes of contamination—and of effective mediation measures—is minimal at best. Universities must continue to conduct research addressing key food safety issues so that the necessary knowledge and tools are available to inform science-based food safety policy.

Rationale for the Global Role of Challenge 4

Although the food supply in the United States is secure and abundant, several factors may lead to food insecurity and decreased abundance in the near future. They include global population growth, climate change, and natural disasters. The United States should play a major global leadership role in addressing such fundamental issues that threaten the very existence of humankind. The average American spends 10 percent of disposable income for food, while people from other developed countries spend from 15 to 25 percent. Those in some developing countries spend up to 50 percent. Significant global food shortage or insecurity can lead to dramatic increases in food expenses in the United States as well as worldwide. Applications of research can result in animals and plants grown for human consumption with enhanced productivity, increased nutritional value, improved efficiency, and greater profitability, in turn enhancing human health, security, and prosperity.

With increased global travel and trade comes increased exposure to foodborne hazards, as illustrated by recent international outbreaks. In 2008, the World Health Organization (WHO) began a 5-year initiative to estimate the global burden of foodborne diseases (Schlundt 2010). More than 2 million people worldwide die from foodborne or waterborne diarrheal diseases annually. Those having weakened immune systems, the elderly, infants, and young children have increased susceptibility to foodborne illness to begin with, and insufficient food and inadequate nutrition weaken them even further. A detailed assessment of the global impact of foodborne illness is essential for efficient targeting of limited resources by policy makers. Investments in education and training, including strategies for adoption and diffusion of research innovations, add greater value and multiple benefits.

Current Capacity and Science Gaps

To ensure future food safety, security, and abundance, the land-grant universities must continue to provide principal leadership in the discovery and application of agricultural and life sciences. As new scientific discoveries lead to new knowledge, that knowledge must be integrated into sustainable global food systems and healthy ecological systems. Scientific capacity hinges on a research and development environment that fosters creativity and innovation and produces economic, environmental, and health benefits that positively impact human life.

Investments in U.S. research capacity in agricultural sciences in general—and in food safety and security in particular—have declined in real dollars over the past 3 decades, despite the continually-increasing global demand for food resources. Science and technology indicators show that proportional U.S. research expenditures are significantly lower than that of many countries having innovation- and technology-driven economies. Some rapidly developing countries, including China, India, Brazil, and Singapore, have aggressive national science and technology strategic plans. Singapore spends 3.5 percent of its gross domestic product (GDP) for research, and China and India are already training more Ph.D.s than the United States. If their growth continues at present rates, these nations will overtake the United States in key science and technology areas.

It is critical that land-grant universities—and indeed, all U.S. research institutions—reenergize the U.S. science and technology enterprise by setting critical priorities, strengthening links between themselves and industry, fostering the benefits of intellectual property, developing capacity by reigniting enthusiasm in young learners from grade school though graduate school, and engaging in key international alliances (Byerlee and Fischer 2002). This ambitious goal can be met only through a targeted, financially-supported policy in which governmental, federal, academic, and private entities join forces and work together.

Much of the U.S. research capacity devoted to a safe, secure, and abundant food supply resides in the land-grant university system, which includes 106 institutions in the United States and its territories. Thousands of projects within the land-grant system deal with issues related to food security, safety, and abundance. However, a careful look reveals serious deficiencies—a major one being the lack of funding for agricultural research. Consider the tens of thousands of **Hatch Act**-funded projects in USDA's Current Research Information System (CRIS) as an example: the vast majority of the projects have minimal funding other than personnel support. Funding for the Agricultural Experiment Station system has been flat for decades. When corrected for inflation, current funding is barely a tenth of that invested decades ago. Although USDA has historically supported multistate collaborative projects, those are typically underfunded. Finally, in light of the charge of this *Roadmap* challenge area, a relatively small fraction of CRIS projects involve international focus or collaboration.

Almost all global science and technology efforts are influenced by the wide gap in research capacity between developed and developing countries. This gap is caused by, among other factors, (a) a discrepancy between scientific resources of developed countries and developing countries; (b) a lack of public understanding and a need for science education and advocacy by the mass media; (c) a lack of integration of theory-building and the adoption of best research practices; and (d) a need for increased multidisciplinary, interdisciplinary, collaborative, and international research initiatives.

Four countries (or regions) are particularly relevant with regard to agricultural production and policy for the twenty-first century. China and India represent exceedingly large population centers, and Brazil is the recognized leader in science and technology in Latin America and has the greatest still-untapped potential for agricultural productivity. The governments of all three of these nations have developed targeted and aggressive science and technology development plans and have supported these goals with significant financial investment in both academic and industrial settings. On the other hand, the countries of sub-Saharan Africa may face the greatest challenges to ensuring sustainable food resources for their citizens (CAST 2010). There is an urgent need for the United States to demonstrate global leadership by recommitting to strengthening scientific capacity, since many countries lack the human resources and infrastructure necessary for successful research programs.

The timing of this *Roadmap* challenge area, which calls for a new emphasis on research to enhance food safety, security, and abundance around the world, could not be better. Food safety, which has emerged as one of the major priorities of President Obama's administration, is being addressed by a White House Food Safety Initiative through the Office of Science and Technology Policy (USDA 2010). Food safety continues to be a top priority for the Food and Drug Administration's Center for Food Safety and Nutrition, and it represents one of the five major foci for research by USDA's National Institutes of Food and Agriculture (NIFA). These new and reenergized initiatives are focused on providing the scientific knowledge needed to develop more effective management policies to minimize foodborne risks throughout the continuum, from farm to table both domestically and globally. The recently-released Agriculture and Food Research Initiative (AFRI) research program includes the priority, *"Radically improve food safety for all Americans,"* echoing the messages presented in this document, and it will facilitate leveraging resources to achieve lasting impact.

Research Needs and Priorities

To meet future U.S. agricultural needs, it will be necessary to develop a strong research agenda and an effective implementation strategy, both of which must include interagency cooperation, multidisciplinary initiatives, and a global perspective. Research discovery must lead to innovations in applications and technology development (CAST 2010) and a much stronger link between academic research and industrial development. Action steps to address future research needs include:

- Develop technologies to maximize the genomic potential of plants and animals for enhanced productivity and quality.
- Develop effective methods to prevent, detect, monitor, control, and respond to potential food safety hazards throughout production, processing, distribution, and service of food crops and animals grown under all production systems.
- Develop more effective tools to trace the origin of microbial, chemical, and physical food contaminants for applications in forensic investigation and attribution.
- Develop food systems and technologies that improve the nutritional values, diversity, and health benefits of food.
- Design strategies and tools to detect and eliminate bioterrorism agents, invasive species, pathogens (foodborne and other), and chemical and physical contaminants affecting plants, humans, and animals.
- Decrease dependence on chemicals that have harmful effects on people and the environment by optimizing effective crop, weed, insect, and pathogen management strategies.
- Identify plant compounds that prevent chronic human diseases (e.g., cancer), and develop and encourage methods to enhance or introduce these plants and compounds into the food system.
- Establish plant and animal breeding programs that balance and optimize nutritional value and complement production characteristics.
- Examine the impacts of changes in the food supply and food transportation systems relative to preservation practices, safety, and energy efficiency at local and regional scales.
- Provide the balanced, targeted scientific data needed for the development of reasonable and effective food production regulatory policies by the USDA, FDA, Environmental Protection Agency (EPA), and other federal agencies.
- Develop stronger links between academic and research institutions and industry to promote the translation of new knowledge into practical applications.
- Develop mechanisms for cooperative international initiatives to enhance food safety, security, and abundance globally.

New Strategies for Education and Training in Multidisciplinary Approaches to Food-Related Issues

To ensure a safe, secure, and abundant food supply for the United States and the world, it is crucial that we adopt strategies for education and training to include:

- Retaining existing and developing new human capital in agriculture.
- Developing educational programs that address needs for increased food production capacity and providing assistance to those interested in careers in food systems.
- Exploring ways to introduce and measure impacts of rural and urban agricultural education, natural resources education, and food literacy education in all schools across the nation.
- Increasing assistance to 4-H, FFA (formerly known as Future Farmers of America), and similar youth programs that integrate environmental and agricultural science into their curriculum.
- Discovering effective educational methods to help individuals make informed and healthy food choices.

It is a daunting task but a sound investment to ensure a promising future.

Expected Outcomes

Given the trends of world population growth, environmental degradation, reduced agricultural labor, and the potential for global bioterrorism, increasing global leadership is crucial to ensure a safe, secure, and abundant food supply. With strategic investments in science research capacity, policy development, and dissemination and coordination of best practices, the Association of Public and Land-grant Universities (A•P•L•U) network will position the food and environmental sector with sustainable solutions.

Investments are crucial for:

- New scientific knowledge that enhances food commodities, minimizes contamination, ensures a secure food supply, and supports effective and reasonable regulatory policies.
- New knowledge that is translated into practical applications through collaborations with industry and close communication with producers.
- Multidisciplinary and multi-institution research that enhances funding efficiency and effectiveness.
- Multinational collaborations and data exchange systems that establish food security and safety.
- National policies for systems-based sustainable production of abundant and safe food.
- Standardized management systems and regulations supported by the United States, the Food and Agriculture Organization of the United Nations, and the private sector.
- Global initiatives that promote research collaboration among universities and research organizations from different countries.

The unique capacities of the American A•P•L•U network and the State Agricultural Experiment Stations and their collaborators are eminently suited for addressing and resolving current issues in food safety, security, and abundance while integrating the need for protecting the environment and natural resources, enhancing food quality and nutrition, and supporting family and rural community development.

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5

Grand Challenge 5

We must improve human health, nutrition, and wellness of the U.S. population.

Framing the Issue

Tremendous health care costs (estimates range from $2.5 to 3 trillion in 2008 and 2009) in the United States drive the need for innovation in medicine and public health. Disease prevention promises tremendous benefits by reducing human suffering and providing cost savings. Improvements in human health through promotion of a healthy diet and lifestyle offer a path forward. A 2007 report by the American Public Health Association (APHA) noted that as obesity and diet-related disease rates increase in the United States, public health is further threatened by food-related issues such as antibiotic resistance; food, air, soil, and water contamination; natural resource depletion; and **climate** change. In order to address these issues, a transdisciplinary approach, encompassing many disciplines, must be used to address food system research and policy issues.

Two primary determinants of health and wellness across the lifespan are access to and consumption of healthy foods and engagement in physical activity (USDHHS 2005, 2008). Over the past 3 decades, the U.S. population has increased energy (i.e., food and beverage) intake, without compensating with increased energy expenditure. This energy imbalance has led to high rates of overweight and obesity in all age groups. Data indicate that 68 percent of the U.S. population (age 20 or older) is either overweight or obese (Flegal et al. 2010). The prevalence of overweight children and adolescents (2 to 19 years old) is also high, with 32 percent at or above the 85th percentile of body mass index (BMI $= kg/m^2$) for age and gender. Seventeen percent of U.S. youth are obese (BMI equal to or greater than the 95th percentile) for age and gender (Ogden et al. 2010).

Since alterations in genetic traits and biological tendencies to prefer high-fat, high-sodium, sweetened foods are unlikely to have occurred within one to two generations, these changes suggest that the social and physical environment have played the most significant role in the recent obesity "epidemic" (Sallis and Glanz 2009; Koplan and Dietz 1999; Koplan et al. 2004; WHO 2004).

Changes in the food environment, and in the physical and social environments in which youth and adults live, learn, and work, have been implicated in the rise of obesity and the subsequent increase in chronic disease over the past few decades (White House Task Force on Childhood Obesity 2010; TFAH 2009). Changes include:

- a low-cost food supply that is high in fat, sodium, and added sugar
- the availability of larger portion sizes, consumed both outside and within the home
- neighborhood designs leading to increased dependence on automobiles and less opportunity to be physically active
- school policies that shorten lunch periods, that allow purchase of sweetened beverages and snack foods to generate revenue, that fail to enforce nutrition standards, and that reduce time for children to be physically active
- decreased daily energy expenditure and sedentary lifestyles due to technological advances such as computers and high definition televisions

The food environment, in its broadest context, consists of three different levels of influence: individual, community, and national or societal. At the individual level it includes places where food is prepared or consumed, such as homes, worksites, schools, and day-care centers. At the community level it includes venues for food purchase, such as grocery stores, convenience stores, food cooperatives, restaurants, and delicatessens. At the national or societal level the food environment is influenced or informed by food and agriculture policies, food systems, food marketing and advertising policies, media, and health care systems (Stang 2009; Story et al. 2008; Glanz et al. 2005).

The primary method for instituting changes in the food and physical activity environments is through policy development. At the community level, policies can improve neighborhood design, and they have the potential to increase recreational activity choices and improve accessibility to healthy foods through farmers markets, **community supported agriculture** programs, and supermarkets and grocery stores. At the state level, policies that aim to improve the school environment could alter the availability of a la carte and vending foods and increase the amount of physical activity available to children and adolescents during the school day. Nationally, policies address advertising and marketing practices and **food safety** issues. Policies are also needed within the workplace to improve healthy eating and physical activity options.

Aging populations in the United States and world wide (USDHHS 2008a) and the concomitant increases in burden from disease and disability associated with aging make it vitally important to implement policies relevant throughout the life span that extend the amount of time older adults will remain healthy, independent, and productive. Age is strongly associated with impairments in activities of daily living, as 40 percent of Americans over age 65 exhibit at least one chronic disease, disability, or other functional deficit that limits normal daily activity. This percentage rises to 90 percent among Americans aged 85 and older (Centers for Medicare and Medicaid Services 2004)—the fastest-growing age group today. As 77 million "baby boomers" swell the ranks of those over 65, the urgency to find new ways to prevent or delay the diseases and disabilities that disproportionately affect older adults is increased. The economic ramifications are sobering: 75 percent of all health care dollars are spent on older adults (Lubitz et al. 2003), and the number of Medicare recipients will grow from 46 million in 2010 to 78 million in 2030 (Kaiser Family Foundation 2008). Our health care system is now shifting to accommodate an older population prone to having multiple morbidities requiring complex (and expensive) care. It is clear that our increasing lifespan must be coupled with an increasing health span to improve human health and wellness.

The application of new technologies to improve nutrition and health promises to increase the health span. For example, nutritional genomics, or nutrigenomics, is the study of how whole foods or food components affect the regulation of our genes and how individual genetic differences can affect the way we respond to nutrients (and other naturally-occurring compounds) in the foods we eat. Nutrigenomics has received much attention recently because of its potential for preventing, mitigating, or treating chronic disease—including obesity, diabetes, arthritis, and certain cancers—through dietary changes that alter expression of key genes. Evidence that exercise plays an important role in prevention or delay of chronic diseases is emerging. It is clearly beneficial to heart and blood vessel health via "**novel mechanisms**" (Joyner and Green 2009). Lack of exercise may contribute to type 2 diabetes, cardiovascular diseases, and certain cancers through failure to activate genes that reduce inflammation (Pedersen 2009). Nanoencapsulation is a technology that can enhance health benefits of processed foods by providing protective barriers, flavor and taste masking, controlled release, and better dispersibility for water-insoluble food ingredients and additives. The microbial flora in the human gut is another important factor in human nutrition. Understanding the role of these organisms in human nutrition is an emerging priority. Once the "total genomic DNA" blueprints of these microbes are available, their roles in human nutrition will be possible to unravel.

One approach to promoting a healthy diet in the U.S. population is enhancing the nutrient content of whole foods. Fortification of processed foods, such as enrichment of grains with folic acid or addition of vitamin D to milk, is a current practice. Selective breeding of plants and cultural practices that increase desirable nutrient profiles are areas for enhancement. Research that couples enhancing nutrient content of whole foods with assessing health outcomes is a priority.

Rationale and Justification

Traditionally, many food-related and lifestyle issues have been viewed and investigated independently, using a single-discipline approach. An alternate approach considers the entire food system, with its interdependent parts providing food to a community, including the production, harvesting, storing, transporting, processing, distribution, consumption, and disposal of food. Potentially, this approach uniquely impacts our food system by strengthening the social fabric of the community as well as the well-being of individuals and families. A number of recent policy statements regarding food and health from a food-systems perspective have emerged from national professional health organizations (APHA 2009; American Dietetic Association Hot Topics 2009; American Planning Association 2009).

Disease prevention and optimal health are, to a large extent, due to behaviors in which individuals choose to engage (or not engage) (USDHHS 2010). It has been estimated that 50 percent of morbidity is due to behaviors that are under individuals' control, while the remaining portion is genetically predisposed. Aging processes encompass factors from the molecular level to the societal level, and these factors affect not only the rate of functional decline but also the means to promote health and maintain quality of life. An understanding of the interactive effects on aging of nutrition, exercise, psychosocial factors, assistive technology, and the built environment has the potential to mitigate declines that are associated with aging. Additionally there is a great need for researchers with the interdisciplinary background required to envision, study, and understand these interactions (Cacciopo et al. 2008) and for professionals to meet the growing needs of older Americans (Institute of Medicine 2008).

Inadequate diet and/or physical activity can be serious risk factors for chronic diseases. The degree to which diet or exercise influences the balance between healthy and diseased states may depend on an individual's genetic makeup. Diet- and exercise-regulated genes are likely to play roles in the onset, incidence, progression, and/or severity of chronic diseases. Dietary intervention based on knowledge of nutritional requirement, nutritional status, and genotype (i.e., "personalized nutrition") can be used to prevent, mitigate, or cure chronic disease. The role of exercise in a healthy lifestyle is another important consideration.

Nanotechnology applications in food include the development of self-assembled nanostructured food ingredients and delivery systems for nutrients and supplements. Nanoparticles include **nanoemulsions**, surfactant micelles, emulsion bilayers and reverse micelles, **nanoparticulated proteins**, self-assembled protein nanotubes, and others. The nanostructured food ingredients are being developed with the goal of offering improved taste, texture, and consistency. A number of nanomicelle-based carriers for **nutraceuticals** and nutritional supplements are currently available. Improving the nutritional value of whole foods through plant breeding and culture is another approach. All of these efforts must incorporate characterization of nutrient profiles and assessment of health outcomes.

Jeffrey Gordon of Washington University in St. Louis sequenced the genomes of about a hundred microbes from the human large intestine. Based on the information from the genomes, it was clear that the microbes in the large intestine degraded plant **polysaccharides**, such as xylan, which cannot be digested by the human host. The microbes ferment these nutrients to produce short-chain fatty acids that are nutrients for the epithelial cells that line the intestinal wall. Short-chain fatty acids such as butyrate alleviated intestinal conditions such as inflammatory bowel disease (IBD). Therefore, these microbes capable of fermenting polysaccharides that are nutritionally unavailable to the host play important roles in energy capture in the gut and also in gut health (e.g., epithelial cells). Some reports also demonstrate that these microbes play a role in obesity. Research in this area would likely advance our ability to influence prevalence of disease conditions such as diabetes and ulcers and also to control energy intake and obesity.

A research approach that considers the entire food system, and that connects agriculture with health and behavioral sciences through education and extension, is required to truly understand the ways in which the food system can improve human health.

Current Capacity and Science Gaps

A systemic approach to food and human health dictates that food quality results from the entire system producing it (Magkos et al. 2003). However, due to the single-discipline-focused nature of research, approaches are often narrowly-focused and uncoordinated, limiting impacts on public health. It is therefore extremely difficult to create concrete messaging to consumers that will empower them to make informed decisions. Clearer and more accurate messaging is therefore needed to assist the public in engaging in proper, healthy dietary decision-making (Clancy et al. 2009).

To date, most of the research addressing improvement of lifestyle behaviors, such as food intake and physical activity, has focused on the individual, the family, or a small group of people in an effort to change knowledge, attitudes, and behaviors. Some of the studies using this "medical model" have successfully produced short-term but not long-term changes in food and physical activity behaviors (Dansinger et al. 2007). It is likely that a significant contributing factor in the lack of long-term success is a lack of environmentally-focused initiatives to support individualized efforts to improve eating and physical activity behaviors within a community or population. Individuals and families cannot successfully implement and maintain behavioral changes if the environment in which they live, learn, and work does not support healthy eating and physical activity.

The majority of studies that have examined effects of food and physical activity environments on the health status of individuals living in communities have been cross-sectional in nature (Black and Macinko 2007; Ford and Dzewaltowski 2008; Giskes et al. 2007; Holsten 2008; Papas et al. 2007). While these studies are useful for discovering potential areas for intervention, they are limited in assessment of causation. Improving human nutrition and lifestyle (particularly exercise behaviors) requires research that validates interventions. Diet and exercise likely prevent or delay chronic diseases through some common and some novel-yet-complementary processes. Carefully defining these can provide rationale for developing practices that yield substantial health benefits.

Technology can enhance food quality. Nanomaterials offer new ways to enhance and stabilize nutrients in food. Phytochemicals act on genes to improve health. Both plant genetics (Simon et al. 2009) and cultural practices (Martinez-Ballesta et al. 2008) influence nutritional profiles of vegetables and other crops. Optimizing nutrient content and beneficial phytochemical content of staple crops for direct human consumption and animal feed offers potential for population-level health benefits. Realizing such benefits requires research that modulates plant phytochemical content through breeding and/or cultural practices, analytical characterization of these whole foods, and research on health outcomes in human populations.

Research Needs and Priorities

- Assess whether organic and other sustainable production systems produce more nutritious or healthier foods. Determine the actual health benefits, if any, of consumption of local foods, and establish standards for defining local foods. Determine the health effects of the use of pesticides, chemical fertilizers, growth hormones, and other chemicals in food production, and determine their effects on the quality of soil, water, and air (Leffall et al. 2010). These studies must consider both statistical significance of the production methods and whether these differences are truly likely to influence human health (Benbrook et al. 2008; Clancy et al. 2009).

- Comparisons of the healthfulness of food products must be made on a per-serving basis and set against an accepted standard, such as the FDA/USDA requirement that a product with a claim of increased nutrient content must contain 10 percent more than a comparison product (Conner et al. 2007). Identify, characterize, and determine optimal serving size and frequency of intake for health benefits of consumption of specific foods containing bioactive constituents.
- Develop community-based participatory methods that identify priority areas within communities that can best prevent obesity in children and weight gain in adults. Develop cost-effective ways of providing healthy foods and adequate physical activity to children in child care centers and schools. Determine what type of knowledge and skills, environment, and support systems help children and adults make healthy lifestyle decisions related to food and physical activity, and assess their impact.
- Using **environmental scans**, determine what design features in the built environment most encourage social interaction, physical activity, and access to healthy foods—especially fruits and vegetables.
- Understand healthy aging via a lifespan perspective, since many influences on the course of healthy aging begin in childhood or even earlier (e.g., Barker 1990). Healthy aging also entails multiple biopsychosocial processes, making it challenging to develop a single definition of "healthy aging" (Ryff and Singer 2009; Young et al. 2009). Develop cost-effective field methods for accurately measuring total energy intake, diet composition, and energy expenditure across the life span. Identify those factors that most contribute to energy imbalance and poor health outcomes.
- Understand factors that contribute to chronic diseases and aging processes. Assess roles of longevity genes (e.g., insulin-signaling genes), regulation of gene expression by diet and exercise, mitochondrial dysfunction and attendant **oxidative stress**, and the efficiency of **apoptosis** (Bostock et al. 2009; Hekimi 2000; Masoro 1999). On a psychosocial level, factors include health behavior habits such as drinking alcohol, smoking, diet, and exercise; social integration and social support of friends and families (Berkman and Glass 2000; Cohen and Janicki-Deverts 2009); and personality (Hooker et al. 2010).
- Assess how cumulative biological and psychological stresses create the "wear and tear" on the body that is known as "allostatic load" (McEwen 1998) and influence resilience in later life (Aldwin 2007). Nutrition may interact with stress to affect physical and mental health in older men and women (e.g., Milaneschi et al. 2010; Tucker 2005). Stress negatively impacts cognitive health (e.g., Lupien et al. 2007; Neupert et al. 2006) in part through its damaging action on the glucocorticoid receptors in the **hippocampus** (Sapolsky 1999). Vitamins and micronutrients may decrease the risk for the development of Alzheimer's disease in later life (Gillette Guyonnet et al. 2007). Identify interventions that buffer the effects of stress on cognitive functioning.
- Investigate the potential of nutritional genomics (nutrigenomics) in personalized prevention or delay of the onset of disease and the maintenance and improvement of health based upon an understanding of our nutritional needs, our nutritional and health status, and our genotype. Nutrigenomics will also have impacts on society—from medicine to agricultural and dietary practices to social and public policies—and its applications are likely to exceed that of even the human genome project. Chronic diseases (and some types of cancer) may be preventable—or at least delayed—by balanced, sensible diets.
- Assess **nanocochleate**-based nutrient delivery for micronutrients and antioxidants. The nanocochleate system protects micronutrients and antioxidants from degradation during manufacture and storage and helps deliver active compounds. Self-assembled nanotubes can offer a new, naturally-derived carrier for nanoencapsulation of nutrients, supplements, and pharmaceuticals (Graveland-Bikker et al. 2006).

- Investigate the metabolic potential of gut microbes after obtaining the **bulk DNA**. Subject it directly to random DNA sequencing. Apply metagenomics, which focuses on studying the metabolic potential of microbes in a given environment based on the contents of the genomic DNA found in that environment. Study gut microbes in their communities without culturing them. This approach can be used to determine what is abnormal in the gut of, for example, someone suffering from gut diseases such as ulcers, and to understand the effect of different nutrients in altering microbial communities to offer a more favorable environment to alleviate the ulcer.
- Expand research on selection and breeding of staple plant cultivars, as well as on cultural practices, to optimize nutrient profiles. Cutting-edge **metabolomic** characterization of these whole foods is an essential element of this work. Assessment of potential health outcomes in appropriate animal models, with subsequent long-term human studies, is another essential element. Identify health-promoting bioactive components of whole foods (including nutrients and other phytochemicals) as well as potentially harmful components, and optimize their plant levels for human health. Few studies have investigated the impact of various agricultural practices on levels of secondary plant metabolites (Asami et al. 2003). These studies should consider the role of genetics, growing environment, and postharvest technologies on levels of these substances (Martinez-Ballesta et al. 2009).

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6

Grand Challenge 6

We must heighten environmental stewardship through the development of sustainable management practices.

Framing the Issue

For much of the twentieth century, U.S. agricultural research focused on increasing production of food, feed, and fiber. That intense focus tended to ignore the impact of agricultural production decisions on **ecosystem** balance. In the coming 20 years, scientific research must lead agricultural landowners and producers toward a new standard that values not only the food, fiber, ornamental plants, and fuel products of agriculture but also the ecosystem goods and services that management of agricultural land, woodlots, and forests can provide. It will be equally important to find production practices that have beneficial effects on the ecosystems with which they interact and that promote human well-being in a broad sense, e.g., less exposure to pesticides, improved water quality, and less risk of disease. To enhance the long-term sustainability of U.S. agriculture for the twenty-first century, research emphasis must be placed on the interrelationships and interactions among agricultural production practices, their regional and global impacts, and the multiple benefits that arise from environmental stewardship.

Forests, wetlands, riparian corridors, deserts, and prairies provide important havens for biodiversity and valuable **ecosystem services,** including water and air filtration, **carbon sequestration**, **nutrient cycling**, and biological control of pests. However, many of these ecosystems are increasingly threatened by **climate** change, invasive species, pollution (including nitrogen deposition), and the use of management practices that pay little regard to long-term sustainability. Land-grant institutions and other participants in the **McIntire-Stennis Cooperative Forestry Program** have also played—and should continue to play—an important leadership role in understanding how terrestrial, aquatic, and biological resources can be managed in a way that recognizes, sustains, and enhances the ecological services and economic benefits they provide. This must be accomplished in the face of multiple and often competing objectives, including the extraction of resources such as timber, fish, and game; the conservation of biodiversity; and the sequestration of carbon—all while protecting soil, water, and the atmosphere. Research is required to determine how best to restore degraded ecosystems and minimize impacts from **agricultural emissions** on the functioning of wildland ecosystems, and in so doing to maintain a set of beneficial functions for human health (e.g., clean water) as well as for aesthetic and cultural values related to biodiversity conservation.

As urbanization continues to increase, it has become increasingly important to design and manage urban forests, lawns, and ornamental landscapes in a way that enhances their sustainability. Urban green areas can provide important ecosystem services, including mitigation of urban heat and stormwater runoff, nutrient retention, and carbon sequestration. When properly designed, ornamental landscapes and urban gardens can enhance biodiversity, including through the conservation of pollinators and natural enemies of pests. On the other hand, turf and landscape maintenance practices can detract from ecological services, depending on how energy, water, nutrients, pesticides, and other inputs are managed. Research priorities should emphasize ecologically-based approaches to landscape design, environmental horticulture, arboriculture, and turf management.

AGRICULTURE AND THE ENVIRONMENT

Agriculture transforms ecosystems and, if not managed properly, can undermine and degrade the integrity of environmental systems, with ensuing negative consequences for human health and well-being.

Resource consumption by industrial agriculture is tremendous. In the United States, food production uses approximately 50 percent of total land area, 80 percent of freshwater, and 17 percent of fossil energy (Pimentel and Pimentel 2003). Competition for these finite natural resources is increasing. In many instances the demand for finite natural resources exceeds the supply, making the rate of resource consumption clearly unsustainable. For example, the rate of ground water withdrawal exceeds recharge rates in many agricultural regions (Hoekstra and Chapagain 2007), while in other regions increased demand from urban communities has reduced the water available for agricultural production. Furthermore, efforts to restore and maintain healthy aquatic ecosystems, essential to supporting fisheries, also contribute to reductions in water available to agriculture. Finally, as global human population and per-capita consumption of natural resources continue to increase, we can expect the greater competition for natural resources to increase the costs of inputs such as energy and phosphate.

Agricultural emissions are substantial and diverse, and they impact every aspect of the biosphere, including soil, air, water, and the organisms living in these environments. Agriculture transforms ecosystems and, if not managed properly, can undermine and degrade the integrity of environmental systems, with ensuing negative consequences for human health and well-being. There is a strong relationship between resource consumption and resulting emissions, with greater inputs leading to increased losses of these inputs into surrounding environments. First, research indicates that agriculture could be a major contributor to global climate change, possibly accounting for significant greenhouse gas emissions, including 52 percent and 84 percent of global anthropogenic methane and nitrous oxide emissions, respectively, as well as considerable carbon dioxide emissions (Smith et al. 2008). Second, the contamination of water resources (both surface and ground waters) with nutrients and other agrochemicals, sediment, and microorganisms has in some areas compromised drinking water and decreased the productivity of aquatic and marine ecosystems, including fisheries and coral reefs. Intensive agricultural systems may also be a major contributor to **marine hypoxic zones** worldwide (Diaz and Rosenburg 2008). Third, long-term productivity of some agricultural lands has been negatively impacted through erosion and through contamination of soils with heavy metals that were prevalent in some pesticides used in the past. More recently, emissions of biotic materials, including escaped organisms and microorganisms and modified DNA, have become a concern in some sectors (Andow et al. 2006). Examples of problematic invasive species originally introduced for agricultural or horticultural purposes include vetches, clovers, radish, and kudzu.

Cascading effects of agricultural resource consumption and its related emissions can undermine the integrity of natural ecosystems and impact humans through a number of mechanisms:

1. *Habitat loss* continues at a rapid rate. The massive share of resources consumed by agriculture—particularly the conversion for agricultural purposes of the remaining highly-productive natural ecosystems and the diversion of water resources—can contribute to widespread losses of plant and animal species and reduces the capacity of natural ecosystems to deliver ecosystem services that support humanity.
2. *Alteration of species composition* has occurred in natural ecosystems due to contamination with agrochemicals, species losses, and introduction of invasive species. Many species

of birds, fish, and amphibians are either endangered or are showing signs of stress caused by exposure to agrochemicals and loss of habitat (Johnson et al. 2007; Mann et al. 2009).

3. *Global climate change* is going to have profound impacts on agricultural production systems in terms of productivity and in terms of interactions with surrounding ecosystems. For example, some areas will be more prone to drought, and this will increase the intensity of water resource competition. In addition, key insect pest problems may intensify as insects increase in distribution or population size in response to the warming climate. And the **thermal balance** of domesticated animals with regard to feed efficiency will be altered due to greater frequency in the occurrence of temperatures that lie outside the **thermoneutral zone** of animals used for food production.
4. *Impacts on human health* from agricultural emissions, particularly through contamination of drinking water and exposure of agricultural workers, have been reported. For example, a study in California found several types of cancer, including leukemia, stomach, cervical, and uterine cancer, were elevated in the United Farmworkers membership in comparison to the California Hispanic population (Mills and Kwong 2001).

The use of a holistic, systems approach can help us to develop new agricultural systems that sustain healthy environments and rural communities. Environmental stewardship needs to be fully integrated into research and management strategies for agriculture and natural resources. Farmers are now being asked to take on environmental stewardship while still using technology and management regimes that reflect an emphasis on yields. Success in developing agricultural systems that effectively provide food and fiber while also meeting environmental goals will require more than simply altering management practices. It will require a systems-based approach to redesigning and restructuring agricultural production systems within an integrated landscape context that considers the mosaic of neighboring ecosystems and natural resources. These two things—the need to maximize productivity while providing a broader set of ecosystem services and the recognition that a new approach to agricultural research is needed to achieve this goal—are the basis for our recommendation to apply the ecosystem services framework and broaden agricultural research goals to explicitly promote the development of multifunctional agriculture.

ECOSYSTEM SERVICES PROVIDED BY AGRICULTURAL SYSTEMS

Recognition of the ecosystem services delivered by the current mixture of agricultural systems and landscapes will provide essential foundational information. This is needed if we are to move forward in redesigning farming systems and agricultural landscapes that can achieve greater environmental stewardship goals.

Current agricultural production systems are often highly productive in terms of marketable commodities, but their capacity to provide other ecosystem services must increase in order to make production sustainable over the long term. The challenge is to maintain high primary productivity and the ensuing agricultural goods (food, fodder, and fiber) of agro- and forest ecosystems, but at the same time to provide other ecosystem functions such as nutrient cycling, the circulation of water, and the regulation of atmospheric composition and soil formation within managed ecosystems and in the surrounding urban and wildland ecosystems.

Ecosystem services are tangible outcomes resulting from ecological processes, and they can be evaluated in economic terms (Costanza et al. 1997; Daly 1997). Shifting the emphasis of agricultural and natural resource research and management to the delivery of ecosystem goods (food, fiber, etc.) and services to society (i.e., water quality and climate regulation) is a powerful concept that is appealing to a wide range of stakeholders. It also serves to bridge gaps among agroecosystem and resource management, economics and markets, and governmental policies.

A rough classification of ecosystem services includes:

- Producing agricultural goods.
- Providing internal services that sustain

the integrity of the ecosystem via soil function and **cross-trophic processes**. Supporting services include conservation of soil structure, prevention of soil erosion, and beneficial species-species interactions such as biological control of pests.

- Ensuring desirable outcomes for ecosystems outside of agricultural fields. Regulating services include generation of ground water, quality of ground and surface water, and atmospheric composition.
- Aesthetic or cultural services.

Table 1 gives some examples of the most commonly identified ecosystem services.

Ecosystem services stemming from managed ecosystems are interrelated, and they occur at temporal and spatial scales that may differ from the production of food and fiber. Regarding their interrelatedness, for example, reductions in nitrogen losses that occur through leaching can result in increased emissions of nitrous oxide if measures focus only on improved water quality without addressing the fundamental problem of excess nitrogen in agricultural systems. Likewise, the addition of cover crops into rotations can enhance multiple ecosystem services; however, in areas where water resources are extremely limited this strategy can increase the need for irrigation and result in reduced water use efficiency. At the same time, research must be scaled to match the spatial distribution and time frame of ecosystem services. For example, the contributions of managed ecosystems to the hydrologic cycle must be considered within the broader context of a watershed rather than at a field or farm scale.

Ecosystem Services	Examples of Benefits
Atmospheric composition	Net carbon dioxide (CO_2) and methane (CH_4) flux; nitrogen dioxide (NO_2) production; carbon sequestration
Soil retention	Reduction of loss by wind, water
Soil formation	Mineral weathering and soil organic matter balance
Provision, storage, and internal cycling of nutrients	Nitrogen (N) fixation, N and phosphorus (P) cycling
Retention of nutrients, breakdown of pesticides	Biological and abiotic assimilation and decomposition
Aesthetic and cultural services	Land values
Hydrological flows	Surface versus aquifer recharge
Pollination	Provisioning of pollinators
Buffer environmental fluctuations	Drought recovery, susceptibility to flooding, fertilizer inputs
Production of harvested goods	Food, fiber, and fodder

Table 1. Ecosystem services potentially provided by agricultural systems.

Sequestration of carbon in stable, **humified soil organic matter** pools is a relatively slow process, and it requires years to decades to quantify carbon accrual in soil. Thus, attention to these multiple functions defines the scales that must be considered in conducting research and developing sustainable managed ecosystems.

MULTIFUNCTIONAL AGRICULTURAL SYSTEMS: A NEW PARADIGM FOR THE TWENTY-FIRST CENTURY

To optimize the contribution of agriculture to society and human well-being, agricultural production systems must be developed with the explicit goal of providing multiple outcomes beyond food and fiber.

The broader view of agriculture's role in delivering ecosystem services is the basis for the concept of "multifunctional agriculture," which recognizes the positive contributions of agriculture beyond food and fiber. In addition to ecosystem services, as discussed above, multifunctionality is usually defined to also include outcomes related to the quality of life for farmers and rural communities. These outcomes include maintaining independent, family farms and strong local economies and supporting rural employment and the continued health of rural culture (Boody et al. 2005; Jordan and Warner 2010). Other multifunctional outcomes include **food security**, landscape values, food quality/**food safety**, and improvement of farm animal welfare. Our emphasis here will be on multifunctionality with respect to ecosystem services relevant to environmental stewardship and their synergies with ecosystem services related to production goals, quality of life, and rural culture.

To achieve the broader goals of multifunctionality and the provision of ecosystem services beyond yields alone, we must apply a new research model in developing and improving food production systems. Research must be systems-based, must include long-term studies, and must include processes occurring at larger scales in order to address ecosystem services that result from diversified landscapes (Boody et al. 2005; Jordan and Warner 2010). In many cases, these ecological and social "goods" will accrue from management practices and land-use patterns at scales larger than individual farms (e.g., watersheds or other landscape-level units). To evaluate multifunctionality, we must apply new metrics and integrated approaches to assess the wide variety of "goods" to society. Measurement of yields or other harvest outcomes needs to occur in terms of other resource use, not just in terms of land area. Yield per hectare is useful; however, we also need to consider yields relative to inputs (e.g., energy, water, and antibiotics) and emissions (e.g., carbon dioxide and other greenhouse gases, pesticides, heavy metals, and other pollutants). We need to apply tools, such as **life cycle analysis** and ecological footprint analysis, to assess ecosystem services. Finally, efforts should also be directed toward the development of sustainability indicators.

Research Needs and Priorities

REDUCE THE USE OF NONRENEWABLE INPUTS IN AGRICULTURAL PRODUCTION

Reducing inputs in agriculture and improving the efficiency of resource use often results in both environmental improvement and greater economic returns. Greater use of tools such as life cycle analysis enables scientists to view the system as a whole and to assess all of the long-and short-term impacts of resource use decisions. Often, improved use of a resource results in reduced losses to the environment. For example, by developing methods to use nitrogen more efficiently in livestock and cropping systems, scientists could substantially reduce atmospheric emissions that contribute greenhouse gases to the environment. Some specific areas requiring increased attention include the following:

Agricultural Water Conservation. This will require developing technologies to improve production efficiencies using less water. We must create new and/or modify existing profitable agricultural and natural resource systems to conserve and recycle water. This includes finding innovative ways to capture and store rainfall and runoff, deliver supplemental water to crops, enhance water recharge value of agricultural and forestry production areas, and promote water reuse in agriculture without compromising food safety.

Protection of Water Quality by Reducing Soil, Chemical, Microbial, and Nutrient Runoff. Hence, there is a critical need to develop practices that minimize runoff and protect ground and surface water. Improved stormwater management and sediment and erosion control, as well as onsite wastewater treatment systems and **wellhead protection** are needed, and public education strategies to disseminate new knowledge to nonagricultural clients will be essential. Land-grant universities must also provide tools and assist watershed managers and others responsible for protecting water resources in implementing technologies and practices to protect or improve water quality at a watershed level. Finally, new tools that enable watershed managers to sample, analyze, and present watershed data—as well as information related to effective selection of policy tools and educational practices—will be required to ensure that water resources are protected.

Energy-Efficient Agriculture Systems, Including Food Distribution Networks and Bioenergy from Animal Manure and Crop Residues. Land-grant universities must develop and implement efficient and sustainable farming and food processing systems that rely on renewable energy systems and that decrease need for nonrenewable forms of energy. In addition to lowering input costs and making food systems more secure, this will lead to rural development and potential income generation. Systems that convert agricultural wastes, such as animal manure, into **biomass** fuels can further improve efficiency of production and reduce environmental impact. New technologies are needed to enable efficient biofuel production from these agricultural wastes. Methodologies for allowing producers to calculate and compare the carbon footprint of alternative agricultural systems must also be developed and used to assess the sustainability of these systems. There is also a great need to study food distribution networks to increase the energy efficiency of distributing agricultural products to markets and ultimately to consumers.

Reduced Air Emissions in Agriculture. Fertilizer is another input to agricultural systems that is impacting air and water quality on a global basis. Current estimates indicate that in some years, on some soils, as much as 50 percent of the nitrogen applied by farmers is not utilized by crops. Nitrous oxide resulting from volatilization of nitrogen fertilizer is a significant source of greenhouse gas emissions. Nutrient runoff from both urban and rural areas has also contributed to the formation of numerous "**dead zones**" in the world's oceans, caused when decomposition of algae blooms stimulated by excess nutrients depletes oxygen dissolved in the water. The use of animal manures for fertility is also causing **euthrophication** in some waterbodies in areas of dense livestock or poultry production. Emissions of nutrients from livestock housing systems represent losses to the environment in the sense that these nutrients could be better utilized if methods for capturing and reusing them were developed. New models need to be developed to predict both atmospheric emissions and their potential impacts in order to stimulate development of agricultural management systems that have reduced air emissions of gases and other atmospheric pollutants.

ASSESS THE CAPACITY OF AGRICULTURAL AND OTHER MANAGED SYSTEMS TO DELIVER ECOSYSTEM SERVICES, INCLUDING TRADE–OFFS AND SYNERGIES AMONG ECOSYSTEM SERVICES

To enable farmers to capitalize on providing ecosystem services through market-based conservation, land-grant universities must evaluate and quantify the ecosystem services provided by agricultural and other managed systems and determine the economic value of these services. The USDA recently established the Office of Environmental Markets (OEM) to catalyze market development for ecosystem services. This represents a substantial new market for agriculture; however, considerable research is needed before these markets become a reality on a large scale. Some studies have also shown that agricultural practices have the potential to decrease the value of goods and services provided by the ecosystems with which they interact. These impacts also need to be explored in greater detail to develop a holistic approach to understanding the contributions of agriculture.

ENHANCE INTERNAL ECOSYSTEM SERVICES (E.G., NUTRIENT CYCLING, PEST CONTROL, AND POLLINATION) THAT SUPPORT PRODUCTION OUTCOMES SO THAT CHEMICAL INPUTS CAN BE REDUCED

Research priorities should focus on development of production systems that protect soil, air, and water quality through an increased understanding of ecological interactions that occur on farms. For example, soil biota (organisms living in soil) are key regulators of nutrient and carbon cycles. And the dynamics of nutrient availability affect not only growth and yield of crops but also their resistance to insects and pathogens. Hence, research efforts should focus on development of ecologically-based soil management practices that reduce nutrient leaching and runoff, increase carbon sequestration, and enhance pest resistance, all while maintaining profitable yields.

With overuse of fertilizers, nutrients are being lost to the environment in an era of increasing fertilizer prices and warnings that the global stock of some nutrients, such as phosphorus and potassium, will last as little as 50 more years at current world use rates. Some warn that, given present trends, relying on gains possible through conventional plant breeding, plow-based cropping systems, and methods for applying plant nutrients will exacerbate rather than improve the impact of agrochemicals on the environment. Reduced-tillage practices have diminished soil erosion and associated agrochemical contamination of surface waters. However, there remains a need to develop profitable strategies that increase nutrient use efficiency in cropping systems including agroforestry, site-specific management, increased crop diversity, and shifting to more perennial crops (integrated crop and animal production, perennial grains, etc.). Precision agriculture technology that targets agrochemical use to where and when chemicals are absolutely required can in some cases further contribute to environmental protection, while minimizing production expenses.

Although important strides have been made in integrated approaches to managing pests of crops and livestock, conventional agricultural production remains highly dependent on pesticides. Although research, education, and regulation have improved pesticide safety, concerns remain about environmental and public health risks associated with their use. Pesticide use can be reduced by continued focus on integrated management of insects, pathogens, and weeds. Ecologically-based weed control is a high priority, especially given the accelerating rate of evolution of glyphosate resistance in key weed species. Conservation of natural enemies of pests through the use of selective pesticides as well as through the use of habitat modification, including companion plantings that provide alternative food sources and refugia (habitats for beneficial insects), can increase the effectiveness of biological control. Production practices should also be evaluated for their impacts on populations and health of honeybees and other pollinators that are critical to maintaining agricultural productivity.

Bioengineering of crops to enhance their pest resistance and stress tolerance continues to hold great potential for decreasing agricultural inputs such as irrigation, fertilizer, and pesticides. However, the recent discovery in India of pink bollworm resistance to **Bt cotton** emphasizes the need for development of crop deployment strategies that delay the evolution of counter-adaptations by pests to bioengineered crops.

ASSESS FOOD ANIMAL PRODUCTION IN RELATION TO ECOSYSTEM SERVICES

Future efforts should focus on the critical issues facing animal systems, including the need to develop livestock production systems that utilize sustainable feeding and pest management strategies, that continue to increase nutrient use efficiency, and that reduce negative impacts on the environment. New opportunities emerging from genomics research could result in novel solutions to vexing production challenges that include the evolution of resistance by pests to management tactics using pesticides and antibiotics.

Although molecular biology is yielding important research breakthroughs, a broader "genes-to-ecosystem" research approach will be required. In such an approach, molecular-based solutions are integrated within a systems-based approach to address pest problems, which often emerge from interactions operating at higher levels of organization, including at the landscape and watershed levels. The notion here is to replace today's chemically-based plant and animal health strategies with more comprehensively organized biotechnologies. This approach would result in novel disease and pest treatments for crops and livestock—strategies that could be much more environmentally friendly.

The food animal industry has two other targets for investigation. Livestock, especially ruminants, produce a large amount of methane gas, which is a more potent (21 times) greenhouse gas than carbon dioxide. Methane emission also accounts for approximately a 6 percent loss of the digested feed, significantly reducing feed use efficiency for human food production. Mitigation of methane emission from ruminants, through dietary intervention or other technologies, will promote environmentally responsible livestock production. Another large-animal-based source of pollution is dairy and poultry enterprises, where a large amount of nitrogen in feed is lost as ammonia in animal waste. This nitrogen wastage creates environmental pollution and increases the cost of dairy products due to the high cost of nitrogen and its inefficient incorporation into the food animals. New strategies are needed to capture ammonia from poultry wastes as well as to manipulate nitrogen metabolism by microbes in the **rumen** through enhanced feeding practices in order to reduce nitrogen waste from livestock production enterprises.

Additional strategic alterations to address nutrient use efficiency must be considered in order to optimize the cycle of nutrients in agriculture, from feed sources to animal waste. Genomics has a significant role to play by altering the genome of an animal so that it uses the nutrients it receives more efficiently, allowing less to go into the environment as waste. Conversely, the diet of the animal can be altered so that the balance of nutrients is beneficial for animal growth and development, with few nutrients remaining to leave in the waste and flow into the environment. Although diet alterations can be implemented without changing the animal itself, altering the genome is an option with long-term implications for animal production. They both must be studied to quantify economics and environmental impact for adoption.

DEVELOP INNOVATIVE WASTE MANAGEMENT TECHNOLOGIES

Animal manures, crop residues, food processing wastes, and other by-products of agricultural production and processing are often organic resources that have potential either to positively or negatively impact the environment. Current systems of handling food-processing wastes are increasingly expensive due to greater disposal costs and stricter environmental regulations. Crop residues represent a large amount of organic material that is available every year for producing products such as fuel, **biogas**, or animal feed. It also can be kept in the field as a source of soil organic matter. However, crop residues could be much more highly utilized. Animal manure is typically stored in on-farm lagoons and then applied to land. Large quantities of these by-products are in need of better management and utilization (e.g., biogas production) to reduce the potential for environmental pollution and to increase economic returns to farmers and processors. Although efforts have been made to recycle many of these materials (e.g., through land application), a great amount remains either underutilized or not used at all. Large accumulations of animal manures have documented potential health and environmental concerns in terms of soil and water contamination, and the atmospheric emissions from these operations are coming under increasing scrutiny from regulatory agencies and concerned citizens. Improved technologies and systems are needed that add value to these resources and that enable transport to areas in need of plant nutrients, all while reducing environmental impacts and carbon footprint.

PURSUE SYSTEMS-ORIENTED AND SCIENCE-BASED POLICY AND REGULATION FOR AGRICULTURAL AND OTHER MANAGED SYSTEMS

Federal and state laws that assure air and water quality, regulate land use, preserve wildlife habitat, assure the well-being of domestic animals, regulate working conditions of food systems workers, impact new food entrepreneurs and processing, impact food safety, and guard against invasive species all impact agricultural efficiency and productivity, at least to some degree. New knowledge is needed to fully understand the trade-offs involved and the broad-scale impacts of various policy decisions and alternatives. A concerted effort is needed to support scientifically sound regulatory decision-making through directed research. Land-grant universities should assume this expanded role.

Policy and regulation driven by systems-oriented, science-based approaches could lead to much improved outcomes. An example of this is the food safety legislation that is currently being considered by Congress. Outbreaks of foodborne illnesses are highly publicized by local and national news media, which often drives quick policy change without a systems or scientific approach to problem solving.

Everyone agrees that a safe food supply is critical. There are concerns that the current debate has framed food safety issues, and possible solutions, too narrowly. A great deal of attention surrounding the safety of fresh produce has focused on microbiological contamination of foods, for example with *E. coli* and *Salmonella*. This biological contamination is only one area

A systems approach can also frame policy directions much differently than a more narrowly-defined approach.

of potential concern for food safety. Fresh produce may also be contaminated during production or processing or in a consumer's home. But an additional concern that cannot be overlooked is the food safety and quality implications of new production systems. Traditional systems operate within a regimen where safe food practices and quality practices are well known, even if they are not always followed. New production systems will require a paradigm shift in safety and quality that will add to their cost, at least initially.

New production systems will require economics research not only on the operations themselves but also on implications related to food safety. Food safety goes hand in hand with all agricultural practices. It will follow developments in production efficiency, sustainability, environmental impact, and animal welfare, as well as the development of new practices. The move from conventional to alternative practices is fraught with barriers to transition, and this introduces lag time into their implementation. Food safety may be seen as one of the barriers, but it is an important one because of the potential economic consequences if it is overlooked or undervalued. An entire system could be vilified by an incident caused by insufficient safety protocols. Such protocols require funding to determine, value, and implement. On the other hand, onerous regulations can work from the other direction to stall transition. Thus, the economic viability and attainment options of alternative production routes need study, especially as they are related to food safety.

Chemical contamination is another potential area of concern with fresh produce. This type of contamination can include cleaning chemicals, naturally-occurring toxins, and pesticides. The last continues to be a food safety concern in agriculture. Pesticide impacts are more difficult to assess as a food safety issue, as they can be associated with more chronic illness (e.g., cancer) compared to the acute illness one might expect in the event of *Salmonella* or *E. coli* contamination. It can be more difficult to pinpoint direct causal relationships, so they are being left out of the current food safety debate, which is unfortunate.

Because of the current consolidation in the food system and national distribution system of aggregated products, when there is a food safety issue that emerges, the negative impact can be nationwide and widespread. There is not only the impact on consumer health and consumer confidence, but in addition, farmers growing the same commodity but completely uninvolved in a particular food safety crisis can also suffer tremendous economic losses and even lose their farms as the outbreak is investigated. For example, in the *Salmonella* scare of 2008, it was suspected for several weeks that tomatoes were the source of the contamination. In the weeks it took to identify the source of the *Salmonella*—peppers from Mexico—Florida tomato producers lost an estimated $300 million, and Florida tomato packers lost an estimated $100 million. These losses were largely due to eroding consumer confidence in tomato safety, which caused restaurants, other food-service organizations, and retailers to quit purchasing tomatoes. A more distributed and regionally-based food system, with systems in place to trace produce back to individual farms, could reduce the widespread impact of a food safety contamination incident on both consumers and producers. A science-based and systems approach could shed light on this.

A major concern for small-scale, diversified farms is that food safety protocols have, to date, taken a one-size-fits-all approach. They fail to consider the certification standards in place that many of these growers already pay for and adhere to. These include organic certification; the scale of producers' operations and the high costs of compliance for small-scale producers relative to large-scale producers; the length of the supply chain to which a given farm contributes; and the risks that are specific to individual crops and production methods. In addition, some of the regulations could run counter to adoption of on-farm conservation measures or could make the sustainable integration of crop and livestock systems difficult. On the positive side, organic certification standards have rigorous manure-management handling protocols already in place that will now be required for all producers who will be food safety certified.

The USDA recently announced a new national initiative entitled, "Know Your Farm, Know Your Food," which supports the development of local and regional food systems. In the words of Agriculture Secretary Tom Vilsack:

> *"…by reconnecting consumers with local producers, we can create new income opportunities for farmers, promote sustainable agriculture practices, help generate wealth that will stay in rural communities, provide families and children with a healthier food supply, and decrease the amount of energy used to ship all over the world…"*

The USDA is responding to a national dialogue now taking place about our current food system. This dialog is prompting a more in-depth look at where and how our food is produced and processed. Who benefits and who does not? What are the costs to our health and the environment? How can the average consumer better understand where his or her food comes from? How do current federal policies (e.g., commodity subsidies) impact or even exacerbate these broader societal questions?

As these important policy debates take place, it is very critical that land-grant universities participate in the decision-making process by providing research-based information that is in the interest of the public good. The only way that this can be ensured is through additional public resources for research in this arena. Already, research at land-grant universities can be greatly influenced by industry support, as other sources of public money have been reduced. This means that for relatively small amounts of funding, industry groups can direct the type of research that gets done as they leverage high amounts of state and federal dollars through the commitment of personnel (faculty, staff, and graduate students) to issues of importance to the industry. Research is thereby directed to solutions that make money for industry rather than to solutions that might be in the best interest of farmers or society as a whole. This problem will continue to worsen without adequate public research money made available to pursue a range of policy and production systems alternatives.

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7

Grand Challenge 7

We must strengthen individual, family, and community development and resilience.

Framing the Issue

Over the past several decades, forces have converged to give a new sense of urgency to the need for research that effectively integrates ecological, social, and economic systems and that heeds and examines the manner in which these interrelated systems affect individuals, families, and communities in America. For example, an August 2009 White House memorandum (Orszag et al. 2009) promoted the importance of embracing both place- and people-based policies and programs for encouraging a vibrant rural America. Rigorous research must guide the development of a strong and resilient rural America. This research must focus on the ties between community viability and family resilience and must build understanding of the core challenges impacting individuals, families, and communities. These critical challenges include internationalization of the economy, global **climate** change, rapid changes in technology and infrastructure needs, population and community demographic changes, new family forms and practices, and increasing pressures on all families in this period of fundamental economic change.

Economic and demographic changes have significantly altered rural America (Irwin et al. 2010). Economically, there has been a steady decline in the industries that traditionally provided the bulk of rural employment. These industries include agriculture, natural resource-based industries, and manufacturing. Loss of employment in these sectors is a consequence of technological developments, lower transportation costs, rising household incomes, and outsourcing to foreign countries to take advantage of lower wages. Other economic changes include housing bubbles, shifts to alternative energy, and the necessity of responding to the most severe and prolonged economic downturn since the Great Depression. At the same time, improved information, communication, and transportation technology have reduced the relevance of location and made it increasingly possible for families and individuals to live where they wish and still be connected globally. As a consequence, economic opportunities now exist in rural areas that simply were not available in the past. Yet, past economic and community development approaches are proving less effective, and the education, skills, and training of many rural workers no longer qualify them for high-quality employment in global economies. The result is continuing high levels of rural poverty and growing gaps between the incomes of those who are equipped with the skills for twenty-first century jobs and those whose skills are linked to declining sectors of the rural economy.

Rural areas have experienced substantial demographic changes. These shifts include growth in amenity-rich and **exurban** areas alongside population decline in many areas historically dependent on agriculture and natural resource employment. Further, dramatic changes have occurred in the composition of the population. Some of the more significant compositional changes include:

The land-grant university system must be ready to prepare an increasingly diverse population for an economy that is much different from the past.

The aging of the population. The proportion of the population that is 65 or older has increased from 4.1 percent in 1900 to 12.9 percent in 2009. The total population of those 65 or older grew from 3.1 million in 1900 to 39.6 million in 2009. As for the nation's **nonmetropolitan** areas, the proportion of the population that is 65 or older has expanded from 15 percent in 2000 to 15.9 percent in 2009 (a growth of more than 670,000 people). Numbers of elderly will continue to increase as the "baby boomers" age. At the same time, the proportion of the population that is 24 or younger declined from 54.1 percent in 1900 to 34.2 percent in 2009. Today, people under 25 now constitute only one-third of the nation's nonmetropolitan population, representing a decline of nearly 235,000 people since 2000.

Rapid changes in the racial and ethnic composition of the population. In the early decades of the twentieth century, about 90 percent of the U.S. population was white, and African-Americans constituted the largest minority group. In recent decades there have been rapid increases of Hispanic and Asian populations. Thus, in four states, (California, Hawaii, New Mexico, and Texas) the white population is now a numerical minority, and census estimates indicate that by 2042, less than 50 percent of the U.S. population will be white. Such diversity is changing America, from youngest to oldest. More than 46 percent of children under the age of five are minority, compared to less than 20 percent of those over the age of 65 (Johnson and Lichter 2010a). In 2009, 48.6 percent of the children born in the United States were minority (Johnson and Lichter 2010b).

Changes in family and household structure. Most significantly, average family size has declined, and there has been a significant decrease in the proportion of married-couple families. In 1950, 78.1 percent of U.S. households were married-couple. By 2000, this proportion had declined to 51.7 percent. There was a corresponding increase in the proportion of female-headed families and non-family households.

Research Needs and Priorities

In response to these economic and demographic changes, it is vital that research, education, and outreach programs be developed to better understand and address the adjustments occurring in rural areas—and the consequences of these changes. The land-grant university system must be ready to prepare an increasingly diverse population for an economy that is much different from the past. As such, existing programs and priorities must be adjusted to meet these new realities. Expanded investments in social science-based research are vital for helping to understand these changing conditions and for ensuring that Extension's outreach education activities are positioned to help people and communities successfully adjust to the new forces at play in rural America. The following are priority areas that should be addressed:

CHANGING ECONOMIC DRIVERS: NEW REALITIES AND NEW STRATEGIES

In the face of a rapidly changing rural economy, there is a lack of understanding about which strategies should be pursued to increase the economic prospects in rural America's communities. Historically, rural economic development efforts have focused on natural resource development or on attracting industrial firms to build or relocate in the community. These approaches are largely outdated in the new global environment. Resource development opportunities are limited, and when an industry builds or relocates, the recipient location is often outside the United States. While the traditional "buffalo hunt" for industrial firms is costly, and the odds of success are quite small, it is difficult to change these strategies without greater understanding of the alternatives.

Conceptual work in rural economics and economic geography suggests that developing "rural capital" (especially human, social, and natural capital), establishing a community's comparative advantage, and building on its unique assets are important elements of rural community development strategy. Yet there is a limited research base on how best to do this.

Hence, considerable debate exists about the relative merits of people-, sector-, and place-based policies and about the roles and efficacy of national, state, and local action to improve rural communities.

Among the critical research questions that need the disciplined analysis of scholars are:

- How can communities determine their comparative and competitive advantage so they can focus energy on developing their unique assets and their niches for economic growth?
- What factors help contribute to the creation and sustainability of regional economic development strategies? What are the benefits and costs of pursuing regional rural development efforts? Are there governance and institutional changes that could benefit rural communities—especially using regional approaches?
- To what extent is growth in the rural hinterland driven by the prosperity of urban centers, and vice versa, and what are the sources of mutually beneficial rural-urban linkages?
- What factors determine the emergence of **“creative” and “knowledge” workers** in rural areas and the building of rural occupational/industrial clusters?
- Given the importance of entrepreneurship and self-employment in rural communities, which local strategies, community policies, and support systems enable entrepreneurs to survive and thrive?
- What are the sources of economic, social, and environmental resilience in rural communities, and how can communities increase that resilience?
- What impact does social capital in rural communities have on economic vitality and resilience, and how can rural community social capital be strengthened?
- Under what circumstances do resource-dependent communities effectively move from extraction and manufacturing to redevelopment based on resource stewardship and benefit from their natural amenities?
- What local actions can enhance the impact of local environmental and other amenities on the achievement of community economic, social, and environmental goals?

STILL LEFT BEHIND: HIGH-POVERTY RURAL AMERICA

For as long as poverty data have been collected, rural areas have had disproportionately higher poverty rates. In 2007, the nonmetropolitan poverty rate stood at 15.4 percent, compared to a national rate of 12.5 percent. Rural child poverty rates are also consistently higher and have been increasing since 1990. In 2007, for example, the metropolitan child poverty rate was 17 percent, compared to 22 percent in nonmetropolitan counties. Poverty for rural children is deeper and lasts longer, and rural children are more likely to live in areas of concentrated poverty (O’Hare 2009). In the rural South, nearly one out of three young children is growing up poor (Mattingly and Seabury—forthcoming*)*. Yet rural poverty has failed to garner the same attention that is given to concentrated poverty found in urban and central-city locations, making rural peoples and places doubly neglected. A substantial body of research documents the obstacles faced by poor rural individuals and families with low levels of human capital and other barriers to economic stability. These individuals are further disadvantaged by limited local opportunities for advancement. Although the number of counties with persistently high poverty rates (20 percent or more since 1970) has been on a long-term decline, they still make up a substantial proportion of nonmetropolitan counties, especially in remote rural areas of the U.S. South and Southwest, Appalachia, and Great Plains and Western Indian reservations (Beale and Gibbs 2006; Lichter and Parisi 2008; USDA-ERS 2010). These areas are characterized by severely stressed local and regional economies, lack of jobs, and high concentrations of racial and ethnic minorities. High poverty rates are accompanied by high levels of food insecurity, low levels of education, lack of access to health care facilities, and absence of other resources and social supports.

Despite extensive efforts to document the forms and sources of rural poverty, major gaps remain in what is known about its unique causes, consequences, and effective remedies, especially as large-scale social and economic change threatens to leave these peoples and places still further behind. Differential impacts of the offshoring of jobs and other manifestations of globalization, new communication and information technologies, population shifts, environmental pressures, and climate change may have unique consequences and pose special challenges for places struggling to recover from dramatically and historically detrimental economic transformation. Weber and his coauthors (2005) propose a research agenda on rural poverty that includes better use of existing data and methods as well as new approaches and data collection efforts that will allow sophisticated modeling of poverty risks and outcomes and include ways to disentangle the influences of characteristics of poor individuals from the influences of their families, communities, and other organizational and institutional factors. This approach must be complemented by qualitative and mixed-methods designs that involve both qualitative and quantitative research. The effectiveness of social programs and policies in rural areas, and whether these differ by type of place, also require further study. A major obstacle to adequately understanding all facets of rural poverty lies in the lack of adequate and timely data for rural social, demographic, and economic analysis. Without better information, rural peoples and places risk being permanently left behind.

High priority questions for future research include:
- What are the impacts of globalization on rural poverty? What characteristics of communities and regions affect these impacts?
- Who are the poor in rural areas with chronic poverty, how do they differ from their urban counterparts, and what are the community factors that block their upward mobility?
- What is the effect for rural poverty of increased employment opportunities in nearby rural communities and urban centers? What types of work supports do the rural poor need in order to enhance their employment opportunities (e.g., transportation, child care, etc.)?
- What is the prevalence, severity, and nature of poverty among those employed in the agricultural sector, and what are the implications of poverty for agricultural policy and employment practices?
- What factors influence the educational and career aspirations of citizens in rural communities? How can the positive factors be enhanced to strengthen human capital in rural communities?
- How does access to information and communication technologies influence opportunities for poor people and communities, and what is the latent potential of this access to ameliorate rural poverty?
- How do population shifts (including the movement of immigrants to new rural destinations) influence poverty outcomes for individuals and communities? What are the particular risks for racial and ethnic minorities in rural areas?
- How will environmental pressures, climate change, and energy demand influence poverty risks and rates?
- What is the relationship between food insecurity and concentrated poverty? How can access to healthy food and health care be improved in high poverty areas?
- What social policies and programs are successful in assisting the rural poor? What characteristics of communities and regions affect the impacts of these policies and programs on rural poverty?

CREATING SUPPORTIVE ENVIRONMENTS: STRENGTHENING RURAL FAMILIES

Family is a valued foundation of rural life, and families comprise 70 percent of rural households (Pruitt 2008). In general, rural families are characterized as more patriarchal than their urban counterparts (Pruitt 2008), are more likely to adhere to traditional gender roles, and are more likely to receive support from family rather than from other members of their informal network (Amato 1993; Hofferth and Iceland 1998). Within this context, parenting is an important role for rural women—a value that can result in personal stress as rural women try to balance mothering and their employment roles (Struthers and Bokemeier 2000). As economic stress increases on rural families, women's earned income is a necessary source of family economic support (Pruitt 2008). Struthers and Bokemeier (2000) state, "the question is not whether women will be workers or mothers, but how they will reconcile the tension between these roles." In 2006, 70 percent of married women with children under the age of six in rural areas worked for pay, compared with 64 percent in urban areas (Smith 2008).

Regardless of their own residence (i.e., rural, suburban, or urban), people often characterize or depict rural family life in an idealized fashion—clean air, safe environments, and open spaces where parents can rear children without fears for their safety. In truth, these characterizations fall short of recognizing a myriad of social issues interwoven into rural family life, including family violence (Grama 2000; U.S. Department of Justice 2007); increasing prevalence of youth gangs (Weisheit et al. 2006); substance abuse; high rates of poverty, especially for female-headed households; limited opportunities for earning a living wage to sustain healthy families; limited and shrinking social services (Lohmann and Lohmann 2005); and homelessness (Rollinson 2007).

Against this backdrop, what are the most salient avenues of research for improving the likelihood that rural communities can provide supportive environments that will strengthen rural families? Three themes can be identified. First, the most pressing issue centers on reducing the persistent poverty that is characteristic of many rural communities. Families cannot be considered strong and healthy when they cannot earn wages that allow for the purchase of necessities. Of the 386 persistently poor U.S. counties, 340 are classified as nonmetropolitan (Jolliffe 2004). In some of these persistently poor counties, current poverty rates are actually higher than those reported during the Great Depression (Pickering et al. 2006). Second, previous research examining rural families has largely focused on two distinct types of families: farm families—a group that represents approximately 6 percent of rural employed residents (Kusmin and Parker 2006), and low-income families—a group estimated to be approximately 15 percent of the rural population (U.S. Census Bureau 2008). Rural areas are increasingly diverse (Hull 2004). We need to increase our understanding of ethnically and racially diverse families; of diversity in family formation and structures, such as intergenerational households and gay and lesbian families; and of how these diverse families interact within their environments to build and support viable rural communities. Third, the complexity of examining rural families and communities involves the reciprocal relationships between the two. Currently, many rural families are "disconnected from the opportunities and supports they need to succeed" (Annie E. Casey Foundation). When rural communities find ways of supporting strong, healthy rural families, these families in turn contribute in multiple ways to a viable rural community. Solutions involve community and regional economic development, community resources to support parental skill-building and educational opportunities, and services to support working families, such as high-quality child care and reliable, affordable housing and transportation.

High priority questions for future research include:

- What are the life experiences of increasingly diverse rural families?
- What factors contribute to community vitality and to strong, healthy families?
- Do diverse rural families differentially experience economic and social opportunities and costs in rural communities? If so, what contributes to the differential effect of these opportunities and costs?
- How do rural communities effectively provide supports that contribute to healthy rural families (e.g., affordable housing and transportation options)?
- To what extent do rural families have access to policies that insure adequate wages and support for working families, such as paid leave, child care, and various tax credits for the working poor?

FIGHTING OBESITY AND REDUCING FOOD INSECURITY: THE IMPORTANCE OF LOCAL FOOD SYSTEMS

Rural Americans have been as susceptible to obesity as those in urban areas. In addition, a number of forces have converged to generate renewed interest from residents and policy makers in food and local food systems. These forces include:

- Concerns with globalized industrial agriculture's impact on **food safety** and the environment.
- Lack of secure access in some communities and neighborhoods to healthy, affordable food.

- Low participation by rural children in federal child nutrition programs.
- Concern about profitability of small-scale farms, particularly in one's own region.
- Concern about conservation of land for agricultural uses in urbanizing areas.
- The alarming rise in obesity in young people and concerns about the health of obese populations.
- Increased interest in the taste and nutritional value of food and in involvement in the preparation of food.
- Interest in enhancing the civic life of communities through the social contacts afforded by farmers markets, **community supported agriculture**, and **food policy councils**.

Much has been learned about the working of the local food system (i.e., Hinrichs and Lyson 2007) and its component parts (e.g., direct-marketing farmers, farmers markets, community supported agriculture, and institutions like food policy councils, food banks, **farm-to-school** and **farm-to-hospital** programs, and place-of-origin labeling). Information is lacking about the economic, social, nutritional, and environmental health effects of our current food production and distribution system and about what can be done at federal, state, and local levels to improve the capacity of the local food system to reduce obesity and food insecurity and build the local economy. Given the interest in local foods, it is surprising that so little is known about how the local food systems actually work, particularly for small producers and low-income consumers, and about how local food production contributes to the local economy, social and civic life, and the natural environment. Understanding these mechanisms and relationships will require new analytic approaches in quantitative research as well as qualitative and mixed-method research. Given the rapidly-changing dynamics of the global and local food environments—and the enterprising spirit of the major actors in these systems—the quality and utility of the research is likely to be greatly enhanced to the extent that stakeholders are involved in the design of the research.

High priority questions for future research include:

- What are the key barriers to **food security** and access to healthy food for low-income populations, and how do these differ for different demographic groups and in different communities?
- What are the key barriers to local food production and direct marketing among small- and mid-sized farmers, and how do these vary by place?
- To what extent is community food security related to the capacity of a community to supply its own food needs?
- What factors determine the capacity of a community to grow and supply its own food, and how can government policy at different levels change the extent to which a community is more self-sufficient in food?
- What are the key determinants of community food security, and how can local action increase the level of food security in a community?
- What structural and behavioral factors influence the effectiveness of community food system practices in achieving local food system economic, social, nutritional, and environmental goals?
- To what extent is the efficacy of federal and state policy that supports local food systems affected by local community characteristics, including geography and climate, natural resources and land use, economic and social structure and conditions, demographic composition, and political and cultural institutions?
- Do local food systems have tangible impacts on rural economies?

STAYING IN TOUCH: THE GROWING IMPORTANCE OF BROADBAND

Large numbers of vacant factories, mills, and industrial parks in many rural places serve as daily reminders that the rural economy is changing and that the magnets for low-wage employment are now located internationally in developing countries (The National Academies 2007; Rosenfeld 2005). The question that local leaders and citizens now ponder is this: "What economic development strategies make sense for rural communities today?" An expanding chorus of researchers is suggesting that the economic prosperity of our nation rests on its capacity to support creative, knowledge-based activities (Florida

2002; Henderson and Abraham 2005; Schramm 2006). The ability of communities to embrace new economic development strategies will depend, in part, on the availability of an array of information and communication technologies. Access to high-speed broadband, in particular, will be indispensable for communities that want to capture and grow knowledge-based enterprises, or that hope to attract **creative and knowledge workers**.

For many communities across rural America, the capacity to be active players in the knowledge-based economy remains elusive, given that rural areas are the least likely to have access to high-speed connections. Recent data show that home broadband use is 14 percentage points lower in rural areas than in urban or suburban places (Rainie 2010). Even when rural broadband service is available, the cost is higher due to limited competition among providers or the higher fixed cost of delivering such service to less-populated areas. No doubt, the new Broadband Technology Opportunities Program (BTOP) being coordinated by the National Telecommunications and Information Administration (NTIA) and USDA's Rural Utilities Service have the potential to put an information technology backbone in place in rural America. But the presence of broadband in rural America is no guarantee that broad-based adoption of broadband will occur. While rural residents have the lowest uptake in Internet use (Pew Internet and American Life Project 2008), the reasons may be linked to the socioeconomic attributes of residents. Better-educated, higher-income people are the most likely to be Internet users, and the largest share of well-educated and more affluent individuals live in urban areas (NTIA 2010). Furthermore, small, micro, and entrepreneurial business owners and managers are the least likely to adopt broadband (Pociask 2005), and an increasing proportion of rural firms is constituted of small, micro, and proprietor-owned establishments.

In light of the vital role of broadband and the accelerated investment being made in broadband penetration in rural America, a number of important research issues demand the attention of land-grant university social scientists, including:

- Does rural broadband access spur local economic expansion? Which industry and occupation sectors benefit the most or the least from broadband? Does broadband accelerate the use of e-commerce strategies by rural firms, and what are the financial benefits (and costs) of using these strategies?
- Does broadband availability promote the growth of creative and knowledge-based workers, firms, or entrepreneurial activities?
- Does broadband expansion increase the uptake in Internet use by rural residents, local governments, and businesses? What individual, family, and community factors impede or facilitate broadband adoption by rural residents, governments, and enterprises?
- What economic and social benefits accrue to rural communities that have broader broadband deployment, such as improvements in health care access or cost, promotion of educational options, and strengthening of civic engagement?
- Will the BTOP accelerate broadband deployment and use by residents and businesses located in historically unserved and underserved rural areas? If not, what core factors are limiting broadband uptake in these geographic areas?

OVERCOMING APATHY: EXPANDING THE CIVIC HEALTH OF COMMUNITIES

Robert Putnam pronounced in his book, *Bowling Alone: The Collapse and Revival of American Community,* that the civic fabric of American communities was in decline (Putnam 2000). His research proved to be a wake-up call for many local leaders and residents who were concerned about the future vitality of their localities. Without question, land-grant universities have long recognized the importance of building the civic infrastructure of local communities. This recognition is reflected in the breadth of community leadership development programs that have been developed and delivered to a host of communities across America (see Flora et al. 2003; Pigg 2002; and Scheffert 2007). Despite these important investments, the reality is that many people remain on the sidelines when it comes to shaping and guiding the strategic directions of their communities.

Is it apathy? Is it the hustle and bustle of everyday life that makes it tough for people to participate in in-depth leadership programs? Is it uncertainty about how best to influence the priority activities of their localities? Or is it reluctance on the part of existing leaders to open the doors of opportunity to new people and new perspectives? Whatever the forces at play, scholars believe that new paradigms for strengthening the civic health of communities are needed to tackle the tough challenges that communities face both today and in the future (Barker and Brown 2009; Sirianni 2009).

The capacity of local people, organizations, and institutions to come together for the purpose of acting on current and future opportunities and challenges is critical to the health of any community. But finding the right mechanisms for building trust, for deliberating on issues, and for acting on key priorities is no easy task in many rural localities. For many areas, strengthening civic engagement is complicated by the upswing in racial and ethnic diversity occurring in many nonmetropolitan counties. Recent research by Putnam (2006) suggests that racial and ethnic expansion can weaken local social solidarity and trust, at least on a short- and mid-term basis. Given that many rural areas have experienced an increased influx of Latinos and new immigrants into the community, there is a real possibility that these communities will struggle in their capacity to work together in tackling the key challenges and opportunities that lie ahead.

It is more than population diversity, however, that is straining the civic health of rural communities. The National Conference of Citizenship (2009) notes that Americans are suffering from a "civic foreclosure." That is, they are compromising the breadth and depth of their civic engagement. The report notes that some of the underlying causes of this trend are the nation's economic recession and the growing mistrust of government, banks, and financial institutions. But the cutback in civic engagement may also be associated with demographic and socioeconomic realities of rural areas. Civic participation is on the decline among older people, low-wealth individuals, and people with less education—the very groups that are a big part of the fabric of towns and small cities in rural America. The quality of educational resources, levels of educational attainment, and personal and community aspirations also have a major influence on overall civic health. Moreover, many rural areas continue to experience the decades-long struggle of losing young adults to out-migration. These are the individuals who would constitute the future leadership of these communities (Beaulieu and Israel 2010; Hamilton et al. 2008; Johnson 2006; National Conference on Citizenship 2009).

Important research is needed to explore viable avenues for spurring a civic renewal among people, organizations, and institutions in rural America. Among the key research questions that would benefit from careful examination and exploration by land-grant university-based social scientists are the following:

- Do investments in civic capacity-building by local governments, educational institutions, or other local institutions advance the ability of rural people to act on community problems and emerging opportunities?
- What types of community leadership development programs are most effective in strengthening leadership capacity within rural communities?
- How can leaders and citizens in rural communities become positioned to embrace and effectively manage positive change?
- Does the incorporation of new modes of civic-centered engagement in rural areas (such as deliberative forums or study circles) mobilize a wider array of local residents to take part in community-improvement activities? Does it enhance trust and collaboration among diverse local populations?
- Are youth who are given sustained opportunities to engage in the civic life of their rural communities more attached to their places of residence? Are they less inclined to out-migrate after completing their schooling?
- Can social media strategies be used by local governments and institutions to deepen citizen awareness and increase input on key local issues? Can it provide a meaningful opportunity for local residents to weigh in on community

matters? Can it strengthen trust between residents and local government agencies and institutions? What individual and structural factors might impede the use of social media as a strategy for boosting civic engagement, especially in rural areas (see Fodil and York 2010)?

UNDERSTANDING ECOSYSTEM CHANGE AND DEGRADATION: INDIVIDUAL BEHAVIOR AND COMMUNITY RESILIENCE

Human systems have contributed to environmental changes, and now human systems need to adapt to predicted and uncertain environmental changes. Understanding the context in which change is occurring, understanding how change impacts the functioning of natural and social systems, and understanding the degree of resilience within rural **ecosystems** are core needs. Social scientists have a critical role to play in understanding the causes of ecosystem change as well as in developing effective strategies and policies for responding to environmental challenges. Social science knowledge is a key to measuring, modeling, evaluating, and predicting the status and future changes of biological systems, **ecosystem services**, and resiliency in rural communities (Antle et al. 2004; Folke 2006). New cross-disciplinary knowledge of spatial and temporal community dynamics will be central to better understanding the important trade-offs that will determine the future condition of communities and ecosystems (Adger et al. 2005; Cumming et al. 2006).

Some key questions related to understanding the links among individual behavior, community institutions, and economic, social, and environmental conditions include:

- How has increased demand for biofuels affected rural communities, and how can federal, state, and local policies be modified to insure that the benefits and costs of these changes are well-distributed across the rural-urban continuum?
- How much does vulnerability of an agricultural region to climate change depend on the area's potential for economic adaptation? What policies might increase the potential for economic adaptation?
- How will increased demand for ecosystem services and alternative energy sources affect rural communities, and how can federal, state, and local policies be modified to insure that the benefits of these changes are well-distributed across the rural-urban continuum?
- What factors increase the vulnerability of rural communities to climate change? What federal, state, and local policy changes can increase community resilience to changes associated with global warming?
- How will increased urbanization and **amenity growth** affect local ecosystems and land use across the rural-urban continuum, and how will it affect the growth and sustainability of rural places? What state-local policy changes can guide land-use change to insure a more balanced spatial distribution of development?

Current Capacity and Gaps

Social scientists have developed a body of knowledge that has improved the lives of people and the vitality of places over the past century. These scientists bring a unique set of tools and analytical techniques to bear on issues that are important to individuals, families, and communities. Social science has informed the life choices of people and families and provided information about the economic, social, and environmental benefits and consequences of these decisions for communities. It has also provided insight into the advantages and disadvantages of alternative federal, state, and local policy decisions as they affect individuals, families, and communities.

Social scientists have well-developed theoretical frameworks for analysis and powerful empirical analytical tools that provide useful and credible answers to policy questions. They use this foundation and these tools in problem identification, assessment of alternatives, and evaluation of potential outcomes of the various alternatives.

The information noted in this Grand Challenge underscores the complexity of improving community viability and individual and family resilience. Without new knowledge and the development of models that enhance our understanding of the interplay among community, individuals, and families, it is likely that much potential progress will not be realized. We believe that there is great potential for exciting research discoveries regarding resilience, resources, and rural people and places—discoveries that will assist federal and local policy makers with the development of programs and strategies that result in equitable benefits to both urban and rural places. The contributions made by social and behavioral scientists should not be minimized as choices are made regarding future investments in *Science Roadmap* recommendations.

The biggest impediment to research on the well-being of rural citizens is a lack of financial resources in the face of significant reductions in research funding. Another major gap in the current capacity to conduct necessary research on rural families and communities is the lack of good data about rural people and places. This takes multiple forms—from the difficulties in obtaining small area data in the American Community Survey to inadequate or entirely lacking rural samples in ongoing panel studies such as the National Longitudinal Surveys—thus limiting the ability to track rural populations over time. There is often little understanding among designers of data collection efforts that rural populations need to be oversampled in order to have adequate sample sizes for reliable estimates. Confidentiality requirements have meant that very small places will get ignored, or merged with larger areas, essentially eliminating their residents' unique characteristics and concerns. The substitution of the American Community Survey for long-form Census data has meant a long wait for information on the smallest places. While this may be partially remedied with its full rollout, the use of multi-year averages for these areas will still create gaps in timely information, and the small sample sizes produce unacceptably large confidence intervals for many rural counties and places. Geographic data need to be routinely attached to data collected on individuals, families, and households, and confidentiality protection protocols need to be developed so these data are not suppressed for small areas. Qualitative studies that provide deeper understanding of the meaning and experiences that lie behind social and economic conditions portrayed in large scale quantitative data analysis are not only critical but essential. Moreover, deployment of new data sources and techniques needs to be considered and planned, or rural areas will fall further behind. For example, the rapid growth of geographic information system (GIS) technologies has opened up a wealth of possibilities for studying spatial influences on individuals, families, and communities, but if rural data collection is lacking or lagging, the problems of rural America will remain under-studied and little understood. The future of rural research on individuals, families, and communities requires support for ongoing data collection on rural peoples and places to compare with what is available for national and urban populations (Tickamyer and Smith—forthcoming).

One way to increase the effectiveness of current investments in faculty is to provide incentives for working with colleagues from various disciplines across the university system. This strategy for filling the gaps in knowledge and improving economic, social, and environmental outcomes in both rural and urban places requires investments in new faculty that can build bridges across disciplines. Such linkages will be required if fundamental advances in the knowledge needed to solve society's most pressing issues are to be realized. New disciplinary strength in the social sciences that can connect with advances in regional science or law, for example, would allow analysis of a broader array of important social questions with economic, social, and environmental dimensions.

Expected Outcomes

Investments in individual, family, and community research will yield solid, policy-relevant information about the forces effecting change for rural individuals, families, and communities. The quality and impact of this research investment will be strengthened with more cross-disciplinary collaboration and with funding structures that encourage the development of long-term institutional research partnerships focused on individual, family, and community well-being. Furthermore, these types of research activities will be crucial to the ability of the land-grant university's Cooperative Extension system to design and deliver outreach programs that are relevant and responsive to the current and emerging challenges that are likely to give shape to the long-term vitality of rural people, families, and places in the United States.

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Appendix A

CROSSWALKING GRAND CHALLENGES

Source	Climate Change	Competitive & Profitable Agriculture	Energy & Bioeconomy	Food Safety & Security	Food, Nutrition & Health	Sustainable Environment & Natural Resources	Other
2009 Science Roadmap Survey	Develop Agricultural Systems for a Changing Global Climate	Develop New Plant Products, Uses, & Crop Production Systems Develop New Animal Production Practices, Products, & Uses Improve the Economic Return to Agricultural Producers Increase Public Awareness of Food, Fiber, & Fuel Production Improve the Productivity of Organic & Sustainable Agriculture Develop Human Capital & Capacity in Agriculture	Develop Renewable Energy & Biofuel Systems	Enhance Production of Safe & Abundant Food		Manage Water Usage Maintain a Sustainable Environment	Enhance the Uses of Bio-technology Sustain Individual, Family, & Community Resilience
Original Science Roadmap Challenges (with 2006 Revisions)	We can lessen the risks of local and global climatic change on food, fiber, and fuel production	We can develop new and more competitive crop production practices and products and new uses for diverse crops and novel plant species We can develop new and more competitive animal production practices and products and new uses for animals We can improve the economic return to agricultural producers		We can ensure improved food safety and health through agricultural and food systems		We can provide the information and knowledge needed to further improve environmental stewardship	We can strengthen our communities and families

(continued)

CROSSWALKING GRAND CHALLENGES (continued)

Source	Climate Change	Competitive & Profitable Agriculture	Energy & Bioeconomy	Food Safety & Security	Food, Nutrition & Health	Sustainable Environment & Natural Resources	Other
Grand Challenges Developed by the Science and Technology Committee at their February 2009 Meeting	Develop Agricultural Systems for a Changing Global Climate		Develop Energy and Materials from America's Renewable Natural Resources	Enhance Safe and Abundant Food for America		Maintain a Sustainable Environment	Enhance Science Capacity and Adoption of Technology Sustain Individual, Family, and Community Resilience Strengthen International Connections
Science and Technology Committee February 2009 Amended List of Undersecretary Buchanan's Grand Challenges	Global Climate Change		Energy Security		Healthy Food and Food Security	Water Availability and Quality	Social, Economic, and Environmental Well-being
Potential Research, Education, and Economics (REE) Roadmap Issue Themes		Agriculture in a Changing Global Landscape Competitiveness and Profitability Changing Global Economy Adjustments to Global Changes Sustainable Agricultural Systems	Energy and Materials from America's Renewable Natural Resources	Safe and Abundant Food for America		Sustaining our Environment	Enhancing Science Capacity and Adoption of Technology Individual, Family, and Community Resilience
Experiment Station Section (ESS) Response to Research, Education, and Extension Office (REEO) Questions	Impacts of Climate Change	Local vs. Nonlocal Food Production and Distribution Livestock Health and Well-Being Plant and Animal Germplasm Collection, Preservation, Analysis, and Distribution	Secure and Renewable Energy Systems	Food Safety & Security		Air Quality Water Quality & Quantity Management of Sustainable Ecosystems	Biotechnology in Society Self-sufficiency for Rural America for Food & Energy Needs

(continued)

CROSSWALKING GRAND CHALLENGES (continued)

Source	Climate Change	Competitive & Profitable Agriculture	Energy & Bioeconomy	Food Safety & Security	Food, Nutrition & Health	Sustainable Environment & Natural Resources	Other
Board on Agriculture Assembly (BAA) FY2011 Budget Themes		Competitive, Productive American Agriculture			Food Systems, Nutrition, and Wellness	Sustainable and Renewable Resources	Human Capacity Development and Education
Experiment Station Section (ESS) FY 2012 Budget Research Priorities/Themes	Climate Change, Mitigation, and Adaptation		Bioenergy, Feedstocks, and Conversion	Food Safety Food Security and World Hunger	Health and Nutrition, Cultural Consumption Practices, Food and Health		
ESS FY2010 AFRI Priorities	Local and Global Climate Change	Economic Return Crop Production Systems, New Products, and New Uses Animal Production Practices, New Products, and New Uses		Food Safety and Health		Environmental Stewardship Agricultural Water	Communities and Families Nanotechnology
Office of Management and Budget (OMB) and Office of Science and Technology Policy (OSTP) Science and Technology Priorities		Applying Science and Technology Strategies to Drive Economic Recovery	Promoting Innovative Energy Technologies		Applying Biomedical Science and Information Technology		Assuring We Have the Technologies Needed to Protect Our Troops, Citizens, and National Interests
Secretary Vilsack's Priorities	National Leadership in Climate Change Mitigation and Adaptation	Sustainable Agricultural Policies		Promotion of a Safe, Sufficient, and Nutritious Food Supply			Building a Modern Workplace with a Modern Workforce Support for 21st Century Rural Communities
Proposed National Institute of Food and Agriculture (NIFA) Institutes	Climage Change and Energy	Plant and Animal Production Systems			Human Health and Nutrition		Human and Community Development
CSREES FY 2010 Budget Priorities	Managing the Consequences and Contributions of Agriculture Practices in Global Climate Change		Sustaining Production of Agricultural Bio-feedstocks for Biofuels and Other Bioproducts		Enhancing Understanding of Community and Behavioral Attributes of Human Nutrition		Assuring the Availability, Quality, and Diversity of a Well-Educated Agricultural Workforce

(continued)

CROSSWALKING GRAND CHALLENGES (continued)

Source	Climate Change	Competitive & Profitable Agriculture	Energy & Bioeconomy	Food Safety & Security	Food, Nutrition & Health	Sustainable Environment & Natural Resources	Other
Farm Foundation 2008 Report on the 30–Year Challenge	Climage Change	Global Economic Development	Global Energy Security	Global Food Security		Competition for Natural Resources	Global Financial Markets and Recession
2009 Strategic Opportunities for Cooperative Extension		Sustain Profitable Plant and Animal Production Systems	Create Pathways to Energy Independence	Ensure an Abundant and Safe Food Sypply for All		Assist in Effective Decision Making Regarding Environmental Stewardship	Prepare Youth, Families, and Individuals for Success in Global Workforce and All Aspects of Life Assist Communities in Becoming Sustainable and Resilient Help Families, Youth, and Individuals to Become Physically, Mentally, and Emotionally Healthy

Appendix B

Science Roadmap Contributors

EXPERIMENT STATE COMMITTEE ON ORGANIZATION AND POLICY (ESCOP) SCIENCE AND TECHNOLOGY COMMITTEE

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CHALLENGE AREA TEAMS

1. We must enhance the sustainability, competitiveness, and profitability of U.S. food and agricultural systems.

Science Leaders
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Casey Hoy (The Ohio State University)
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2. We must adapt to and mitigate the impacts of climate change on food, feed, fiber, and fuel systems in the United States.

Science Leaders

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3. We must support energy security and the development of the bioeconomy from renewable natural resources in the United States.

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4. We must play a global leadership role to ensure a safe, secure, and abundant food supply for the United States and the world.

Science Leaders

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5. We must improve human health, nutrition, and wellness of the U.S. population.

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6. We must heighten environmental stewardship through the development of sustainable management practices.

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7. We must strengthen individual, family, and community development and resilience.

Science Leaders

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Glossary

Within the Introduction and the Grand Challenge areas, the first instance of glossary items is set in **bold type**.

A

abundant food supply. See *food abundance*.

agriculture. In the context of this document, agriculture is defined in its broadest sense and includes food production and associated activities; natural resources including forests, rangelands, wetlands, water, and wildlife; and the affecting social, cultural, and environmental factors.

agricultural emissions. The movement of materials and organisms from *agriculture*—at any point in the production chain—into the biosphere. Agricultural emissions include nutrients from fertilizers, agrochemicals, heavy metals, greenhouse gases, sediments, and organisms or their DNA.

amenity growth. Population growth occurring as new residents move to a community seeking features such as *weather* and *climate*, open space, and scenic views.

apoptosis. Cell suicide in response to damage or other stimuli; programmed cell death.

Association of Public and Land-grant Universities (A•P•L•U). A non-profit association of public research universities, land-grant institutions, and state university systems with member campuses in all 50 states, U.S. territories, and the District of Columbia.

B

bioeconomy. Refers to an economic system where the basic building blocks for industry and the raw materials for energy are derived from plant/crop-based (i.e., renewable) sources.

biogas. Gas produced by the biological breakdown of organic matter in the absence of oxygen. Processes such as anaerobic digestion and fermentation produce biogas, which often consists of some quantities of methane or other combustible gases that can be used to produce energy.

bioremediation. Remediation of environmental perturbations using plants or microbes.

biomass. Plant materials and animal waste used especially as a source of fuel.

biopolymers. Polymers produced from a biomass source. See also *polymers*.

blend wall. The limit at which refiners can blend standard gasoline with ethanol and/or other biofuels. The Energy Independence and Security Act of 2007 (Pub. Law 110-40) requires the U.S. motor fuel supply to contain 36 billion gallons of ethanol and advanced biofuels by 2022 (known as the *Renewable Fuel Standard* [RFS]). In most regions of the country, ethanol blends may contain up to 10 percent ethanol, which is believed to pose no significant problems to the existing gasoline dispensing and storage infrastructure. Here is where the "blend wall" comes into play. The nation consumes approximately 145 billion gallons of gasoline each year, and approximately 120 billion gallons are subject to the RFS ethanol blending formula. Even if every gallon of gasoline included in the RFS were blended with 10 percent ethanol, refiners would hit the "blend wall" at around 12 billion gallons. Refiners are expected to hit the ethanol "blend wall" between 2011 and 2012 (at the current 10 percent ethanol blended consumption).

brownfield landscapes. Lands where redevelopment or reuse may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant.

Bt cotton. Cotton that has been genetically modified by inserting the gene coding for producing the bacterium *Bacillus thuringiensis* (Bt) to produce a chemical harmful to a small fraction of insects that damage the cotton plant.

bulk DNA. Total DNA isolated from a mixture of species contained in a sample.

C

carbon sequestration. The natural removal of carbon from the atmosphere as carbon dioxide by the soil and plants. This process can be increased in agricultural systems with practices such as cover cropping and reduced tillage intensity.

cellulosic fuels. Fuels developed from plant and animal biomass sources. Cellulose occurs naturally in plants and is the chief constituent of their cell walls. Cellulose is also the source of many manufactured goods.

climate. In simplest terms, climate refers to long-term "weather averages." This can include the average frequency of extreme events, such as the average number of heat waves per year over several decades. The World Meteorological Organization considers the statistical mean and variability of factors such as temperature and precipitation over a period of 3 decades to evaluate climate trends, but climate can refer to other periods of time, sometimes thousands of years, depending on the purpose. See also *weather*.

community supported agriculture (CSA). An increasingly popular way for consumers to buy local, seasonal food directly from a farmer. Optimally, consumers benefit by getting fresh produce, and both farmers and consumers benefit economically by avoiding the middleman.

coproducts. Valuable secondary products that arise in the production process of biofuel development. For example, distiller's grain is a coproduct of ethanol production and is used as an animal feed.

creative and knowledge workers. Individuals involved in jobs where they are expected to be creative and innovative by drawing on complex bodies of knowledge.

cross-trophic processes. Interactions across trophic levels, such as herbivory (where an animal eats a plant) or predation (where an animal eats another animal, such as a lady bug eating an aphid).

crosswalk. To crosswalk information is to compare data characteristics from one information system to that of another information system.

D

de-hardening. Loss of cold hardiness (tolerance to cold) in perennial plants due to a period of warm temperatures that reverses or partially reverses the physiological process of cold acclimation.

E

ecosystem. An ecologically-defined unit of the biosphere consisting of organisms and their environment.

ecosystem services. The products and services humans receive from functioning *ecosystems*, both managed and natural, including harvested products such as food and fodder, clean air and water, flood control, *nutrient cycling*, wildlife habitat, habitat to support biodiversity or species at risk, *climate* regulation, soil formation, soil carbon storage and sequestration, and other human uses such as viewscapes, hiking, camping, and other recreational activities.

emergy. A form of analysis similar to *life cycle analysis* that considers embodied energy.

environmental scan. Documenting the social and/or physical environmental features that support or hinder healthful food/diet and physical activity/exercise behaviors among target populations.

euthrophication. An increase in the concentration of nutrients, such as nitrogen or phosphorus, in a water body to an extent that rapid growth of phytoplankton or algae occurs. Negative environmental effects include, particularly, anoxia (loss of oxygen in the water) with severe reductions in fish and other animal populations. While euthrophication can be a natural process, it is often accelerated by increased nutrient loads to a waterbody.

exurban. Scattered, low-density, and generally upscale residential areas beyond urban and suburban regions.

F

farm-to-hospital. Programs where farmers sell their produce directly to local hospitals. Hospital benefit by having fresh produce, and both farmers and hospitals benefit economically by avoiding the middleman.

farm-to-school. Programs where farmers sell their produce directly to local schools. Schools benefit by having fresh produce, and both farmers and schools benefit economically by avoiding the middleman.

feed conversion efficiency. A measure of an animal's efficiency to convert feed mass into increased body mass.

feedstocks. The type of plant materials or animal waste used as the source for fuel or other bioproducts developed from *biomass*.

flex-fuel vehicles. Vehicles specially designed to run on standard gasoline or any blend of up to 85 percent ethanol (E85).

food abundance. Denotes a food supply of sufficient quantity, nutritive value, and variety to support the quality of life experienced by most Americans and people in the developed world.

food desert. Locales that lack access to stores or markets that sell food needed to maintain a healthy diet. These locations often have a surfeit of fast-food establishments.

food policy councils. These local organizations bring together stakeholders from diverse food-related sectors to examine how the food system is operating and to develop recommendations on how to improve it.

food safety. Denotes reasonable freedom from intentional or unintentional biological, chemical, or physical agents in the food supply that can cause injury to consumers.

food security. Denotes a continually available supply of food of sufficient quality to sustain life. It also encompasses adequate nutrition provided in culturally acceptable forms.

functional foods. Foods that contain, or are "engineered" to contain, enhanced nutrition, such as one or more compounds that are beneficial to human health.

H

Hatch Act. The Hatch Act of 1888 created experiment stations associated with the colleges. These developments led to the expansion of research plots that established the value of fertilizer in crop production and defined the variations in soil management requirements across the country. Retrieved from **http://www.answers.com/topic/soil.**

hippocampus. Brain region within the cerebral cortex linking sensory experience and emotion.

humified soil organic matter. Organic matter in soils that has been modified or decomposed to the point of stability. The process is similar to composting: microorganisms modify plant materials and convert them into a dark brown material, which is humus. Much as in composting, organic matter in the soil is converted to humus through the humification process.

L

life cycle analysis. A methodology that identifies the environmental impacts associated with the life cycle of a material or product in a specific application, thus identifying opportunities for improvement in environmental performance. See also *emergy*.

lignin. A complex chemical compound and an integral part of the secondary cell walls of plants. It is one of the most abundant organic *polymers* on earth, exceeded only by cellulose, employing 30 percent of non-fossil organic carbon and constituting from between a quarter to a third of the dry mass of wood. See also *cellulosic fuels*.

M

marine hypoxic zones. Areas near the coastline that have low levels of oxygen and generally do not support aquatic life. These zones are often caused by increases in nutrients (particularly nitrogen and phosphorus) that cause algal blooms that deplete the oxygen in the water column.

McIntire-Stennis Cooperative Forestry Program. Forestry research supported by federal funds allocated to schools of forestry, land-grant colleges, and agricultural experiment stations under the McIntire-

Stennis Cooperative Forestry Research Act of October 10, 1962 (Public Law 87-788).

metabolomics. Chemical characterization of the metabolic profile that a biochemical pathway or multiple pathways produce.

N

nanocochelate. Complex of two or more solids that are each of a particle size of one-tenth of a micrometer or less in one dimension.

nanoemulsion. A suspension of droplets one-tenth of a micrometer or smaller in at least one dimension in a solution.

nanoparticulated proteins. Protein particles one-tenth of a micrometer or smaller in at least one dimension.

nonmetropolitan. A metropolitan area contains a core urban area with a population of 50,000 or more and includes the counties containing the core urban area as well as any adjacent counties that have a high degree of social and economic integration with the urban core. Any county that is not metropolitan is defined as nonmetropolitan. It is a common practice to consider nonmetropolitan counties as "rural."

novel mechanisms. Descriptions of new concepts for processes that underlie biological events.

nutraceuticals. Food constituents with health benefits in addition to nutrition value.

nutrient cycling. The use, transformation, movement, and reuse of nutrients such as nitrogen and phosphorus in an *ecosystem*. Nutrients are retained and recycled through different organisms (e.g., nutrients are exchanged between plants and bacteria in the soil).

O

oxidative stress. Accumulation of reactive oxygen species in a tissue in excess of antioxidant capacity.

P

photobioreactor. A bioreactor that incorporates some type of light source to provide photonic energy input into the reactor.

phytoremediation. The use of plants to remove unwanted compounds, minerals, etc. from soils.

polymers. High-molecular-weight compounds, either natural or synthetic, composed of repeating chains of smaller, simpler molecules. A *biomass*-based production process can replace the traditional oil-based production process in the creation of polymers and other valuable bioproducts from agricultural material. See also *biopolymers*.

polysaccharide. A molecule composed of a chain of sugar residues; a starch.

process heating. The use of a *coproduct* as a fuel stock in the production process of biobased fuel.

pyrolysis oil. A synthetic fuel under investigation for use as a substitute for petroleum. It is extracted by *biomass*-to-liquid technology of destructive distillation from dried biomass in a reactor at a temperature of about 500°C, with subsequent cooling.

R

receptor. A protein molecule or complex that reacts to a chemical messenger with a signal that triggers a physiological response.

Renewable Fuel Standard (RFS). Created under the Energy Policy Act of 2005, establishing the first renewable fuel volume mandate in the United States. It lays the foundation for: achieving significant reductions of greenhouse gas emissions from the use of renewable fuels; reducing imported petroleum; and encouraging the development and expansion of our nation's renewable fuels sector.

rumen. The first chamber of the alimentary canal of ruminant animals (e.g., cattle, goats, and sheep). It serves as the primary site for microbial fermentation of digested feed.

S

scale dependence. Refers to the fact that the efficiency and effectiveness of technologies vary significantly depending upon the scale of operation.

steady state economy. An economy of relatively stable size with no appreciable growth or decline.

T

temporal discounting. The tendency of people to put lower value on rewards (i.e., benefits) that are more distant from the present compared to rewards that can be attained closer to the present. This tendency can also occur with regard to assessment of costs and risks.

thermal balance. All animals have a *thermoneutral zone* at which production is maximized, since in this zone they do not need to expend energy on heating or cooling. If ambient air temperatures change, energy is transferred from functions such as growth or reproduction to heating or cooling the animal in a balancing process.

thermoneutral zone. The thermoneutral zone for an animal is the ambient temperature range where no extra energy must be expended by the animal to maintain its body temperature. If ambient temperatures are outside this range, the animal will need to expend energy to warm or cool itself, resulting in decreased productivity.

tile drainage. A system of below-ground porous pipes designed and installed in a field to drain water from the field and thus prevent prolonged flooding in the root zone and surface.

translational research. Translational research brings scientific discoveries arising from laboratory and field to practical applications.

W

weather. The atmospheric condition (e.g., temperature, precipitation, humidity, wind) at any given time or place. In most places, weather is highly variable and can change from hour-to-hour, day-to-day, and season-to-season. In contrast, climate refers to long-term averages of weather. See also *climate*.

wellhead protection. Groundwater wells are particularly sensitive to contamination at the soil surface immediately surrounding the well (wellhead). Measures to protect this area include management practices, such as not mixing or storing chemicals or nutrients near the well, and structural practices, such as maintaining the well casing and placing impermeable curbs around the wellhead.

Experiment Station Committee on Organization and Policy

Experiment Station Section
The Board on Agriculture Assembly
Association of Public and Land-grant Universities (A•P•L•U)
http://www.aplu.org