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Sustainability of Biofuels
Future Research Opportunities

Report from the October 2008 Workshop

USDA

U.S. Department of Agriculture
Research, Education, and Economics

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Sustainability of Biofuels Workshop

State of the Science and Future Directions

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http://genomicsgtl.energy.gov/biofuels/sustainability/
http://www.ree.usda.gov/

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Executive Summary

Legislative mandates and incentives, volatility in oil prices, and new research and technological advances are driving the expectation of major increases in the production of biofuels from cellulosic biomass. To assess the current state of the science underlying the sustainability of an emergent cellulosic biofuel sector and to identify further research needs, the U.S. Department of Agriculture's Research, Education, and Economics mission area and the U.S. Department of Energy Office of Science cosponsored a workshop on October 28–29, 2008. Although the term "sustainability" has been defined in many ways, common to these definitions is the theme of meeting the needs of present and future generations. Sustainable biofuel production is economically competitive, conserves the natural resource base, and ensures social well-being. This report summarizes critical research areas and knowledge gaps relevant to the environmental, economic, and social dimensions of biofuel sustainability. It also underscores the critical need for a common socioecological framework to develop a systems-level understanding for how these dimensions interact across different spatial scales—from the small plot or farm to regional to very large scales such as political, national, and global scales. In addition to forging a responsible path for implementing cellulosic biofuels, much of what can be discovered about biofuel sustainability will provide important insights into successful future agricultural and forest production—the dependable and abundant supply of food, fiber, and feed.

Environmental Dimensions of Biofuel Sustainability

The four dimensions of environmental sustainability research in this report are (1) soil resources and greenhouse gas emissions; (2) water quality, demand, and supply; (3) biodiversity and ecosystem services; and (4) integrated landscape ecology and feedstock production analysis.

High-yielding feedstock production systems require soil resources that allow sufficient root penetration and provide adequate nutrient and water supplies throughout the growing season. Soils also can play a role in mediating climate change by storing carbon and providing habitats for microbial communities that influence greenhouse gas emissions or help promote efficient production of plant feedstocks that can be converted into biofuels. Some key research opportunities include using advanced microbial genomics to enhance soil fertility and reduce greenhouse gas emissions, characterizing and modeling soil carbon and nitrogen cycling processes for different biofuel feedstock production systems, developing improved biofuel feedstock production systems, and predicting how soil and plant processes will respond to climate change. Also needed is the development of field-deployable instrumentation to quantify nitrous oxide and methane fluxes.

Up to now, most research on cellulosic feedstocks has focused on optimizing growth conditions and feedstock productivity. Research is needed to determine the impacts of biomass feedstock production on water quality and availability within different ecoregions where biofuels will be produced. The impacts of biofuel production on water quality, demand, and supply will vary considerably by region, depending upon competition for water supply, the type of biomass feedstock and how it is managed, characteristics of the land, and the local climate, including potential future changes. Research will help determine the potential impacts of converting existing managed and natural landscapes to bioenergy feedstock production and developing regional assessments of water requirements and impacts for a wide range of feedstocks and management practices.

Biofuel production systems will be a part of larger landscapes that provide a variety of ecosystem services important to society and the environment. In addition to crop productivity, control of greenhouse gases, and reduction of water contamination, biofuels could increase biodiversity and supply critical habitats for beneficial organisms. As well as gaining a more comprehensive understanding of the effects of different biofuel production systems on the provision and regulation of ecosystem services, analysis frameworks are needed for modeling and bundling some of the most highly valued services for optimal multifunctional benefits.

Landscapes used for biofuel production will be characterized by complex interactions with a large number of ecosystem components that act together in important but as-yet incompletely understood ways. Information is needed at intermediate watershed and regional scales of resolution, and research will be critical to understand and improve models of ecosystem biophysical properties and their interactions and integration with economic and other human behaviors.

Economic Dimensions of Biofuel Sustainability

An active area of economic research is determining the mix of cellulosic feedstocks likely to be competitive in different regions, the spatial pattern of land-use changes that the use of these feedstocks will induce, and implications for food prices. Although existing economic models can predict aggregate land-use change, more precise estimates—particularly at smaller scales—will require additional research. Further research on indirect land-use effects will help resolve implications of increased production of feedstocks. Life cycle analyses should be improved to capture more accurately a comprehensive real-world representation of the ancillary effects of management scenarios. In addition, economic analyses are needed to examine the costs and benefits of policies to achieve biofuel production goals and to determine possible unintended consequences.

Social Dimensions of Biofuel Sustainability

The social implications of the emergence of cellulosic biofuels represent some of the most pressing and challenging sustainability issues. Research to understand how stakeholders may respond based on their values, choices, behaviors, and reactions will be critical to the development of a biofuel sector. Careful consideration must be given to social structures and policies that can promote or inhibit development of expanded biofuel production. As with biophysical considerations, adequate analyses will be necessary to understand how social processes function at multiple scales and with complexity—from individual farms and forests to whole communities and regional ecosystems—so science can inform decision making and design at local, regional, national, and global levels. Research is needed to identify feedstock production systems, biorefining processes, and enterprise structures that fit the needs and values of different communities and to optimize benefits for biomass producers, biorefiners, and encompassing communities by improving local conditions and reducing undesirable consequences.

Research to understand stakeholder needs and motivations will help define preferred societal outcomes. A diverse portfolio of decision aids, education, communication tools, and outreach and extension activities will be needed to enable stakeholders to make decisions based on information supported by environmental, economic, and social science research.

1. Introduction

The U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) held a Sustainability of Biofuels Workshop on October 28–29, 2008, in Bethesda, Maryland. Its purpose was to assess the current state of the science and to identify further research needs in the effort to develop a sustainable biofuel economy.

The workshop was jointly hosted by USDA Under Secretary for Research, Education, and Economics Gale Buchanan and DOE Under Secretary for Science Raymond L. Orbach. DOE and USDA have the joint goal of informing the debate surrounding the sustainability of biofuels by providing sound science through strategic investment in research programs. This report describes issues addressed at the workshop and identifies critical areas and knowledge gaps that can be advanced by further sustainability research. The report also summarizes research opportunities identified by workshop participants and is organized around themes based on the three dimensions of sustainability:

- Environmental
- Economic
- Social

Although "sustainability" has been defined many different ways, underlying all these definitions is the common theme of meeting the needs of present and future generations while conserving the natural resource base and ensuring social and environmental well-being. The sustainability of biofuels (or any product) spans environmental, economic, and social dimensions that interconnect.

One strong message from the discussions was the need for a common socioecological framework for the study of sustainability and for a systems approach across scales. Successful biofuel development will depend on understanding the complex, integrated nature of sustainability. This knowledge must be used to build a new biofuel sector by considering production costs and environmental outcomes, as well as local, regional, national, and global needs. In addition to forging a path for implementing cellulosic biofuels "the right way," much of what can be discovered about biofuel sustainability will provide important insights into the successful future production of food, fiber, and feed. Success will require an integrated, holistic approach to research and implementation that cuts across the environmental, economic, and social aspects of biofuel sustainability.

No single feedstock type or land-management practice will work for all locations. To understand the kinds of feedstocks and management regimes that would be best suited for different landscapes, it is necessary to envision the complete system—from production, management, and processing to ecosystem services, and from economic outputs to infrastructure and resource requirements for local production of different feedstocks. Research needs range from genomic tools that target soil microbial communities to those that measure the state of natural resources under different production scenarios and tools to understand the social and economic implications of decisions that influence the selection and implementation of biofuel feedstocks.

Research will be needed to address ways to determine impacts at diverse scales from the molecular level to entire regions of the country. Tools will be needed for integrating and extrapolating information derived from all operational scales. For example, just as more needs to be understood about how water use is regulated at a fundamental molecular level by a particular feedstock, more also needs to be understood regarding the impacts of how managed inputs such as fertilizer applications may influence nitrate loading from edges of fields, the quality of water at a small watershed scale, and, to a greater extent, the impact of summer hypoxia events in large receiving water bodies.

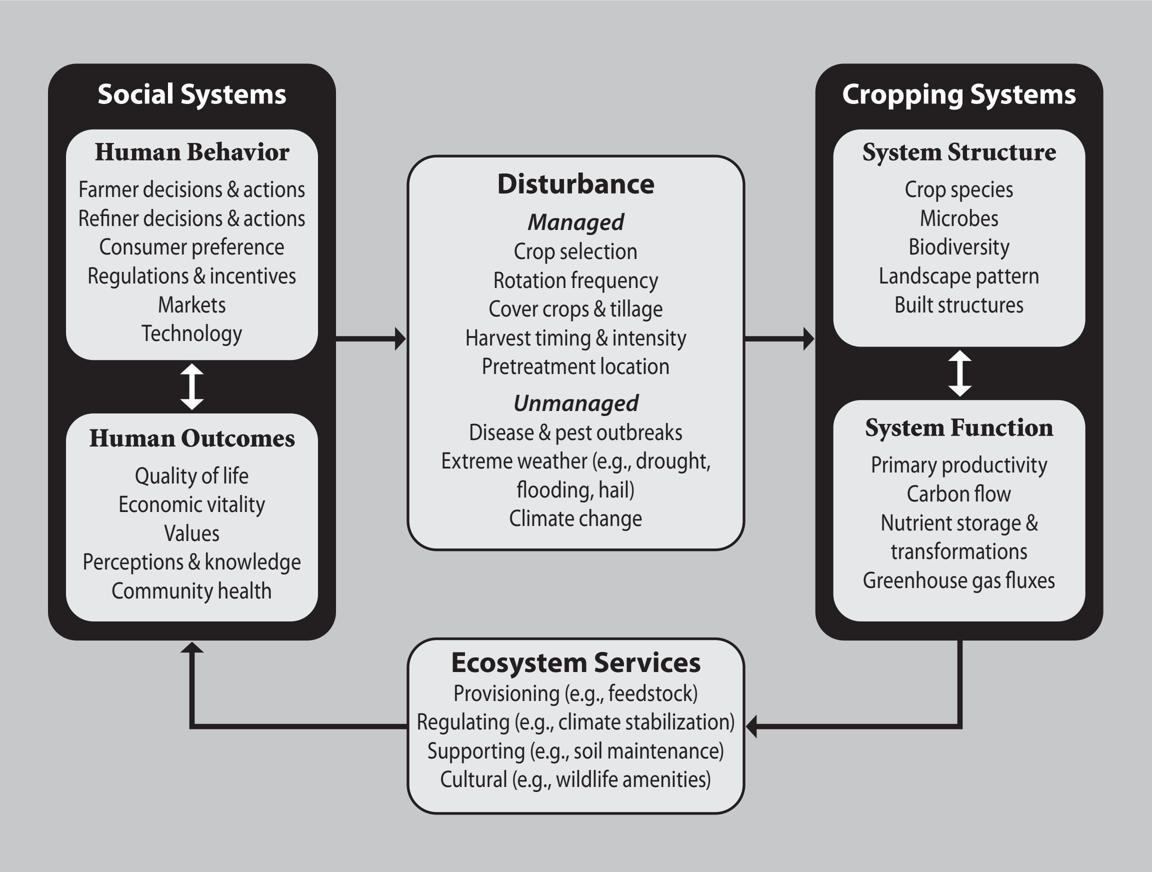
Biofuel production has regional and global implications on food, fiber, and feed production and for the provision of ecosystem services such as soil and water quality and biological diversity. Choices of biomass feedstocks, cultivation and harvesting practices, and technological changes could have a variety of potential impacts. Research is needed to develop models to predict the most significant outcomes that could ripple through interconnected ecological and societal systems. The illustration (see sidebar, Socioecological Framework for Biofuel Systems, p. 7) describes a cyclic framework in which cropping systems provide ecosystem services, which are valued by society through economics and other social systems and consequently affect management choices for the cropping systems.

Growth of the biofuel sector will take place in a dynamic fashion influenced by changing environmental, economic, societal, and technological factors. For example, the cost that society is willing to incur for contaminated runoff, loss of soil fertility, erosion, and disruption of wildlife habitat may change. Innovations from material science and biotechnology are likely to lead to major advances in energy feedstocks and fuel products. Population growth, climate change, globalization or localization of energy and other markets, and changes in the way energy is generated (distributed versus centralized) also will have significant impacts. Research is needed to understand how this dynamic environment will impact future opportunities and needs for biofuel use and development.

Successful expansion of cellulosic biofuels requires new transformational technologies that address challenges to sustainability such as reliability of abundant feedstock supplies; land-use change and competition; cost reductions for growing, harvesting, and transporting feedstocks; the efficiency of feedstock conversion; and the production and utilization of conversion by-products. Research is needed to ensure the development and availability of integrated production systems that are flexible in the face of evolving innovations, developing knowledge, and identification of best practices.

Research is needed to develop decision-support tools that help decision and policy makers weigh alternatives, anticipate likely outcomes, identify important factors and tradeoffs, and quantify uncertainties of decisions at the farm, forest, community, regional, national, and global scales. For example, a tool that helps select the best location to site a biofuel production facility might incorporate information on feedstock availability, type, and growth rates; infrastructure; capital and labor markets; and tax structure. Similarly, science-based performance measurements

Socioecological Framework for Biofuel Systems



After Robertson et al. (in prep.) after Collins et al. 2007

Currently, most analyses and ecological modeling of biofuels focus on the biophysical aspects of the cropping systems and conversion technologies used for biofuel production. Developing sustainable biofuels, however, will require understanding how biofuel production will influence and be affected by interconnected social systems, including economics, and ecosystems. The figure above shows how managed and unmanaged disturbances shaped by human behaviors can impact cropping systems and associated ecosystem services, which, in turn, feed back into the social system affecting human decisions, behaviors, and outcomes. Research that provides a comprehensive view of the interactions among bioenergy cropping systems, social systems, and ecosystem services is needed to develop science-based informational resources that can support decision making at local to national and global levels. [Source: After Robertson et al. (in prep.) after Collins et al. 2007. *Integrated Science for Society and the Environment: A Strategic Research Initiative.* Publication #23 of the U.S. Long-Term Ecological Research Network (LTER), LTER Network Office, Albuquerque, New Mexico.]

for farm and forest management and biorefinery operation are needed to compare outcomes at all levels from local to global.

1.1. Driving Forces for Biofuel Development

Countries and companies across the globe are investing extensively in biofuel development programs, motivated by concerns and opportunities related to global climate change, energy security, and economic development. Many countries have ambitious biofuel targets or mandates.

Grain-based biofuels already provide some nations with a renewable energy resource that has produced new jobs and economic development opportunities. Agricultural and forest producers, biorefiners, and policy makers anticipate that cellulosic biofuels have the potential to achieve ambitious national goals for biofuel production. Sound science, technology, economics, and policy development will be needed to ensure the sustainable production of cellulosic biomass, including intensification and potential expansion of agricultural and silvicultural practices to meet the demand for biofuels, conserve or enhance natural resources, and benefit farm and forest economies and rural communities.

In the United States, the diverse goals for accelerated production of biofuels from agricultural and forest resources are reflected in a series of recent U.S. policies: the Biomass Research and Development Act of 2000, the Energy Policy Act of 2005, the 2002 and 2008 Farm Bills, and the Energy Independence and Security Act (EISA) of 2007. As part of EISA, the Renewable Fuel Standard (RFS) mandates that 36 billion gallons of biofuels are to be produced annually by 2022, of which 16 billion gallons are expected to come from cellulosic feedstocks that will need to be produced from working lands on a large scale (see sidebar, Land Requirements for Biofuel Production, p. 9). EISA also includes a variety of incentives for the demonstration and deployment of biofuel production technologies, including biorefinery plant construction and operation, and describes requirements and subsidies for the use of biologically derived ethanol in gasoline blends. In addition to provisions for biofuel production, EISA recognizes the importance of biofuel sustainability by mandating a life cycle analysis for biofuels every 2 years and the development of sustainability criteria and indicators. The Food, Conservation, and Energy Act of 2008 (P.L. 110-246, 2008 Farm Bill) includes incentives and programs for accelerating cellulosic feedstock production and cellulosic biofuel production and refining.

With the recent surge of national and political support for the large-scale development of bioenergy alternatives to fossil fuels, some of the most important issues arising from the potential paradigm shift for bioenergy production are the environmental, economic, and social implications. Subsequent chapters in this report summarize output from workshop participants and identify key challenges, knowledge gaps, and research opportunities specific to environmental, economic, and social dimensions of biofuel sustainability.

1.2. Sustainability and the Emerging Cellulosic Biofuel Industry

The emerging cellulosic biofuel industry—if driven by science-based strategies that conserve or enhance the natural resource base, increase economic viability, and build societal acceptance—offers the potential for new sustainable outcomes that have not been achieved with existing grain- and petroleum-based systems alone. Agricultural and forest landscapes that will be called upon for this next generation of biofuels need to be viewed as sources of multiple benefits, including biofuels (Jordan et al. 2007). Such benefits include carbon sequestration, conserved and enhanced soil productivity, reduced greenhouse gas emissions, and increased economic development of rural communities.

Feedstock production systems designed around improved crops and practices could require less fertilizer and perhaps less water, trap nitrogen and phosphorus that otherwise would be transported to groundwater and streams, and accumulate carbon in both roots and soil organic matter. Effectively managed, these feedstock systems additionally could enhance ecosystem services such as natural insect and disease pest suppression, water-quality protection, and cultural and wildlife amenities. However, these potential benefits are not guaranteed. Uninformed or short-term decisions about how, when, and where cellulosic feedstocks and biofuels are produced could limit progress toward a sustainable bioenergy future (Robertson et al. 2008).

Land Requirements for Biofuel Production

Land area in the United States is about 2.3 billion acres. Around 1 billion acres are used for agricultural purposes (including grasslands, pasture, and croplands); 650 million acres are forest-use lands; and the remaining portion is devoted to parks and wildlife areas, urban areas, and other miscellaneous uses (Lubowski et al. 2006). About 340 million acres of agricultural lands are active cropland with corn, soybeans, and wheat representing around two-thirds of this area. Even with the recent growth in corn ethanol production, only about 18% of the grain harvested from 87 million acres of corn in the United States was used for ethanol production in 2007, while more than half of harvested corn grain was used for animal feed (USDA/NASS 2008; USDA ERS 2008).

The 2007 Energy Independence and Security Act Renewable Fuels Standard has mandated the production of 16 billion gallons of cellulosic biofuels by 2022. To meet this target, cellulosic biomass will need to be harvested from America's working lands on a large scale. By one estimate, 16 to 19 million acres of energy crops are needed (Biomass Research and Development Board 2008).

2. Environmental Dimensions of Biofuel Sustainability

Ensuring that the emerging cellulosic biofuel industry is sustainable requires careful consideration of environmental dimensions. Soil quality, which is determined by a complex collection of biogeochemical processes, is important to protect for both current and future crops and thus is a key area for research. Similarly, an accurate accounting of greenhouse gas emissions associated with different types of feedstock production is necessary to understand the impact of cellulosic biofuel production on ecosystem health and the quality of natural resources. In addition, the increasing pressures on water supplies nationwide are expected to continue, requiring research to minimize water use by biomass crops, as well as nutrient and other contaminant runoff. Another important research area involves understanding the role of biodiversity in maintaining ecosystem services and developing necessary strategies to ensure that as the production of biofuels increases, adequate supplies of other needed agricultural and forest-based goods are produced. Finally, fully understanding the potential impacts of biofuel production on landscape ecology and systems interactions requires expansion of field experiments and modeling studies beyond the small-plot and field scales to regional scales with appropriate validation and interpretation using real-world biophysical, economic, and social conditions. Each of these areas of environmental sustainability research is discussed more thoroughly in the following sections of this chapter. Using genomics and systems biology approaches to improve potential bioenergy crops and obtain a mechanistic understanding of the biological processes underlying bioenergy feedstock development is important, but it was not a focus for this workshop. Biological feedstock development research topics are presented in the report *Breaking the Biological Barriers to Cellulosic Ethanol*, based on a workshop convened by the U.S. Department of Energy in late 2005.

2.1. Soil Resources and Greenhouse Gas Emissions

Soil is the foundation of plant production. It determines the kinds of plants that can be grown; the need for water, organic matter, and nutrient amendments; and the outcomes that result. High-yielding production systems can occur only when the soil provides an adequate water supply throughout the growing season, allows roots to penetrate the soil profile to use nutrients and water, and presents minimal limitations to plant growth and development. Soils also can play a role in mitigating climate change by enhancing carbon storage and by providing habitat to support microbes that generate or consume the greenhouse gases methane and nitrous oxide.

When feedstock production systems are not managed to protect soil resources, degradation can occur, resulting in soil loss due to water and wind erosion, reduced water and nutrient availability, and deterioration of soil structure that can limit rooting depth, aeration, and water movement. Additionally, stored carbon can be released back to the atmosphere through natural processes and production management practices. As biofuel feedstock production expands, research is needed to determine how crop and forest production systems might be made more efficient while at the same time maintaining or enhancing soil productivity.

Many cellulosic feedstocks are perennial (either as a monoculture or polyculture), and, consequently, roots are always present to help reduce soil erosion and retain nutrients. Research is needed to determine how perennial plants, their root structure, and associated microbial communities impact belowground carbon allocation and greenhouse gas production. Research focused on improving quantification of soil carbon and nutrient cycling processes, including the movement of carbon through short- and long-lived soil carbon pools, is needed to better understand and manage systems to conserve soil carbon. Also important is research to better define relationships among soil carbon storage and the fluxes of non-CO_2 greenhouse gases under perennial crops.

Climate variability lies at the crux of optimizing feedstock production systems. To effectively manage plant productivity and soil carbon processes, research is needed to better understand potential changes in precipitation and temperature patterns, atmospheric carbon dioxide concentrations, nutrient availability, and resistance to disturbances.

Understanding Interactions among Soil, Microbial, and Plant Processes

Plants are complex systems in which biogeochemical interactions occur among the carbon, water, and nitrogen cycles and the microbes that live around the roots, on leaves, and as endophytes living inside the plant. Atmospheric CO_2 is taken up by plants through photosynthesis. Although some of this carbon is respired back to the atmosphere, a portion is incorporated into plant material distributed above and below ground. Nonharvested plant material becomes soil organic matter (SOM), which is linked to the water cycle as it impacts infiltration rates and the soil's water-holding capacity. These two cycles, in turn, are linked to cycles of nitrogen and other nutrients crucial for plant growth and development.

Microbes in the plant environment can fix nitrogen, mineralize nutrients from decaying organic matter, scavenge phosphorus, produce plant growth promoters, aid soil structure, and protect against disease agents. These functions help improve biofuel feedstock production efficiency while also ensuring sustainability of the soil resource. Control of soil microbes could play a beneficial role in increasing the production system efficiency of biofuel crops. On average, a third of the nitrogen used by sugarcane can be acquired via a nitrogen-fixing system (Boddey et al. 2003; Polidoro 2001; de Resende et al. 2006). Some of these bacteria also produce hormones that stimulate plant growth (Baldani and Baldani 2005). Research to understand and apply these and other strategies could result in increased production efficiency of dedicated energy crops with reduced dependence on synthetic fertilizers.

Enhancing Carbon Storage

Research on biogeochemical processes that influence carbon storage and fluxes in soils may also lead to decreased emissions of CO_2. Carbon storage is controlled by the soil environment and the quality of the organic matter in which the carbon resides. Maintenance of optimal soil water and temperature regimes results from soil management strategies that protect the soil microenvironment and promote an environment conducive to beneficial microbial activity. The addition of organic matter and maintenance of soil cover can improve soil quality by building SOM and can thereby lead to higher plant productivity and other environmental benefits.

Minimizing Net Non-CO_2 Greenhouse Gas Emissions

In addition to CO_2 emissions, another important area of research is to understand the non-CO_2 greenhouse gases methane and nitrous oxide that are associated with biofuel production. Although CO_2 is the most abundant greenhouse gas, both methane and nitrous oxide are more potent, with global-warming potentials much higher than that of CO_2. In general, nitrous oxide releases increase with the addition of excess nitrogen fertilizer and thus can either decrease or eliminate the greenhouse gas benefits of a biofuel operation.

Besides greenhouse gas emissions, various levels of air pollutants—carbon monoxide, volatile organic compounds, fine particles, and sulfur oxides—are released on end use, depending on the type of biofuel blend used for combustion. In general, air pollutant emissions from biofuel combustion tend to be lower than those from the combustion of petroleum-based fuels. Although these pollutants have important air quality and human health impacts, they were not a key focus for this workshop.

Measuring Flows and Stocks of Greenhouse Gases

New monitoring and instrumentation will be necessary to measure, predict, and manage the flows and stocks of CO_2, nitrous oxide, and methane in biofuel systems. Net soil CO_2 release is commonly inferred from soil carbon change, which means that carbon stored in soil will need to be estimated carefully, including its form and persistence.

Harvesting Biomass While Maintaining Site Productivity

Research on the influence of biofuel crops and management strategies on soil fertility will help improve plant productivity. Expanded crop yields require the efficient use of carbon, water, nitrogen, and other nutrients by the plant, which, in turn, requires a soil resource capable of supplying water and nutrients to meet plant requirements.

Soil protection measures should be integrated into biomass production methodologies. Research is needed that includes long-term soil-quality monitoring to help assess changes in physical, chemical, microbial, and other biological properties, thereby providing critical information for designing management systems to support bioenergy production (Wilhelm et al. 2007), habitat restoration, and the reduction of wildfire risk.

There also is substantial interest in using accumulating forest biomass for biofuels. In the western United States, biomass buildup as a result of fire suppression and insect and disease outbreaks on federal lands is a primary motivator for removal. Converting this buildup into cellulosic biofuel could help suppress unmanaged wildfires, improve stand health, and meet cellulosic feedstock needs.

Research is needed to develop appropriate harvest and collection systems to protect site hydrology and soil structure and productivity.

Reducing Net Greenhouse Gas Emissions from Cultivation and Harvest Practices

Research is needed to determine impacts of the cultivation and harvest of cellulosic feedstocks on greenhouse gas emissions in order to improve those practices. Conservation tillage farming can reduce erosion, and, when carried out over long periods of time, it can improve soil carbon content. Net greenhouse gas emissions can be reduced by conservation tillage even when combined with the application of nitrogen fertilizer (Archer and Halvorson 2009, in review). More research on options to integrate bioenergy crop production with existing row crops could reduce the greenhouse gas footprint for traditional agriculture by decreasing the need for fertilizers and minimizing carbon and nitrous oxide emissions from soils.

Research Opportunities

- **Improve biofuel crop performance and soil fertility by understanding and manipulating microbial communities.**
  - Use genomics and other advanced methods to better characterize the function of microbial communities in plant-soil systems, including the rhizosphere, foliar, and endophytic microbes involved in carbon and nitrogen cycling, disease suppression, and other services.
  - Develop improved understanding of the biotic and physicochemical factors that control the distribution, abundance, and effectiveness of these microbes, including interactions with organisms in other trophic levels and how these affect the production of biofuel feedstocks and other agricultural and forest products.
- **Predict and manipulate soil carbon cycling and sequestration.**
  - Investigate differences among candidate biofuel management systems with respect to belowground carbon cycling and potential rates of carbon sequestration.
  - Characterize the biochemical nature and recalcitrance of sequestered carbon and its importance for soil structure and nutrient and water availability, while also developing an improved understanding of the biotic and physicochemical factors that control the persistence of sequestered carbon and how these are influenced by management.
- **Evaluate and develop improved biofuel feedstock production systems.**
  - Build improved quantitative models of carbon, nitrogen, and water cycles in biofuel feedstock production systems to predict productivity and environmental outcomes from field to landscape scales. Create a means to link biophysical models to land-use, economic, and other socioecological models in order to simultaneously forecast the outcomes of alternative policy and land-use decisions in different biophysical, socioeconomic, and soil domains.
  - Identify and understand response thresholds, such as the reaction of soil carbon or microbial communities, to differences in the rate of agricultural or

forest residue removal or to differences in the intensity of management through fertilizers or other inputs. Identify other biology-based management strategies that reduce the need for agricultural inputs.

- Determine how to identify resistance and resilience of different systems as challenged by biogeochemical or technological change, as well as the mechanisms responsible for these differences.

■ **Predict responses of soil and biomass productivity to climate change.**

- Build on existing experiments and infrastructure to predict how agricultural and forest ecosystems will respond to climate change and changes in atmospheric chemistry. Use multiscale infrastructure from fields to farms to watersheds and regions so precipitation, temperature, and other environmental factors can be manipulated to understand their interactions and significant impacts on systems.

■ **Understand how soil microbial populations and activity influence methane and nitrous oxide consumption and fluxes to minimize emissions.**

- Use genomic and other advanced approaches to characterize how soil microbial communities respond to management and are responsible for nitrous oxide production and methane consumption.
- Determine how changing biotic, physical, and chemical factors control soil microbial distribution, abundance, and capacity to produce and consume trace gas and determine how populations can be controlled for more sustainable outcomes.

■ **Model nitrous oxide and methane fluxes to identify strategies that will reduce emissions from cropping systems.**

- Conduct long-term field experiments to characterize fluxes in soil carbon during the establishment and production phases of cropping systems and in response to changing annual and longer-term environmental conditions. Quantify long-term trends in nitrous oxide and methane fluxes in cellulosic biofuel systems and the environmental and management factors that regulate fluxes at different temporal and spatial scales across U.S. ecoregions.
- Refine and validate mechanistic models of nitrous oxide and methane fluxes for different biofuel cropping systems in an appropriate variety of climate and soil domains. Incorporate soil management and best management practices into landscape-level models to allow the prediction of fluxes with land-use change. Develop and test decision support tools that can be used by producers and decision makers to design high-mitigation biofuel systems.
- Develop field-deployable instrumentation for quantifying *in situ* nitrous oxide and methane fluxes that are highly variable in both space and time. Use these systems to test and calibrate models, as well as in field experiments where rainfall, temperature, and other environmental factors are manipulated to understand the interacting effects of environmental change on fluxes.

- Improve approaches to greenhouse gas mitigation by quantifying differences among candidate biofuel management systems with respect to energy as well as nitrous oxide, methane, and other greenhouse gas balances.

2.2. Water Quality, Demand, and Supply

Numerous human activities including industrial processes, urbanization, timber harvest, construction projects, agriculture, and landscaping projects affect water quality (National Research Council 2008). Discharges from these activities contribute to varying degrees of water-quality problems with local and downstream effects on rivers and water bodies. An expansion of biomass and biofuel production will likely affect water quality, demand, and supply. Impacts will vary considerably by region, depending upon competition for water supply; the kind of biomass feedstock and the way it is managed; characteristics of the land; local climate, including potential future changes; and methods used to convert biomass to biofuels.

Some choices of crops and cultivation options could cause soil and nutrient loss and require large amounts of irrigated water. However, options that include cellulosic feedstocks such as woody vegetation (e.g., intensive, short-rotation forestry) and perennial herbaceous species (e.g., switchgrass) have the potential to be produced and harvested in ways that reduce water runoff, soil erosion, and nutrient and pesticide exports to surface and ground waters. Prior research on cellulosic feedstocks has focused on optimizing growth conditions and feedstock productivity. Future research is needed on the impacts of biomass production on water quality and availability. The current lack of knowledge limits our ability to make decisions on the efficient use of water, the control of runoff, and the ability to assess water-quality and water-supply implications for the different cellulosic feedstocks that will be suited to different growing conditions around the country.

Water Quality

Current agricultural practices impact the quality of the nation's water supplies. The extent of sediment and nutrient loss from fields is largely determined by management practices. Practices such as tillage and annual crop production on erodible lands can cause erosion and sediment deposition. Conservation tillage, the integration of perennial cover crops between the rows of annual crops, and the use of native grasses as vegetative filter strips and riparian buffers surrounding annual crops can substantially reduce nutrient and sediment export in agricultural watersheds.

Much can be learned about land-use designs, site preparation, and use of conservation management approaches to reduce surface runoff, erosion, and the export of sediments, nutrients, and pesticides from biofuel feedstock crops (Biomass Research and Development Board 2008). This should be linked to research on crop growth including soil-related processes that enhance plant nutrient availability and reduce input losses.

Watershed-scale models have been used to predict water-quality changes resulting from conversion of corn or other annual crops to switchgrass in the midwestern

United States. (Biomass Research and Development Board 2008; Vadas, Barnett, and Undersander 2008; Nelson, Ascough, and Langemeier 2006). Model results for Iowa, Kansas, and the upper Mississippi River basin suggest that 17 to 43% of current cropland could be converted to switchgrass, reducing erosion by 20 to 90% and decreasing nitrogen and phosphorus export up to 60% if fertilizers are not used. However, models indicate that nitrogen and phosphorus export from switchgrass fields is highly dependent on the amounts of fertilizer applied. When excessive fertilizers are applied to switchgrass fields, nutrient export is comparable to that seen in row crops. Watershed-scale research is needed to assess the aggregated impacts of agricultural production and conservation systems (Richardson, Bucks, and Sadler 2008) and to determine the impacts of incorporating bioenergy production.

Although there is a long history of research on the impacts of forest management on water quality, with the emergence of the biofuel industry, relatively few studies have examined the water-quality relationships of forests managed specifically for bioenergy production. Conversion of unmanaged forests to biofuel production could produce negative effects depending on where these lands are located and how they are managed. An East Texas study of intensive forestry impacts indicated significant increases in storm runoff, erosion, and nutrient loss relative to controls, but the impacts were highly variable over time (harvest cycle, weather) and with different management practices (site preparation, burning) (McBroom et al. 2008a; 2008b).

Water Demand and Supply

U.S. agriculture is the second-largest consumer of water from aquifers and surface supplies. The future biofuel production industry will create new demands on the quantity of water used by agriculture and production forestry. Globally, commercial bioenergy production is projected to consume 18 to 46% of the current agricultural use of water by the year 2050 (Berdes 2002). Population growth and changes in land and how it is used will influence future demands. Water requirements for processing biomass into biofuel also are important, but the quantity of water consumed by processing facilities is considerably less than that consumed by crop cultivation and thus was not a focus of the workshop.

In many parts of the United States, the agricultural sector already faces water shortages. In the arid West, agricultural withdrawals account for 65 to 85% of total water withdrawals. In the East, supplies are under pressure from competing uses, especially in periods of drought. Although overall withdrawals in the United States have decreased since 1980 and efficiency improvements are still possible in irrigation, the amount of water needed for a biofuel-based energy supply is much greater than equivalent fuel production from fossil fuels.

The understanding needed to assess future impacts of cellulosic feedstock production on the water supply will require investigation of mixed feedstock production systems that vary by location and could be difficult to monitor. Although some water inputs from rainfall or irrigation are incorporated into crop biomass, water is lost primarily through plant transpiration, evaporation, runoff to surface waters, and deep percolation beyond the reach of plant roots. Evapotranspiration rates vary by feedstock, genetics, and weather. Current watershed models may not capture these field-scale effects at the basin scale.

Research is under way at the watershed-scale level to develop the methods needed (Steiner et al. 2008) to understand the implications of future biofuel production on systems and make science-based decisions that will lead to greater sustainability. Also, results of forest conversion experiments from long-term monitoring catchments (e.g., gauged catchments on experimental forests within the U.S. Forest Service) are providing historical data that can be used for improved models. Research is needed to expand methods and information systems to extend evapotranspiration, runoff, and infiltration models from watershed scales to greater regional scales across the entire country. Furthermore, the combination of life cycle analysis and environmental cost accounting with watershed hydrological and water-quality modeling will provide improved tools for analyzing the water requirements of feedstock supplies as well as biofuel conversion plants. A critical research need will be examining how the expansion of biofuels and more intensive agriculture will affect the water cycle and future precipitation patterns, especially within the context of the uncertainty in future climate change.

Research Opportunities

- **Understand water-supply requirements to improve prediction and management.**
  - Develop hydrological models that reflect the effects of converting agricultural crops, forests, and other land uses to bioenergy feedstock production under a variety of management conditions. Validate model predictions with data obtained from field and watershed studies.
  - Determine the influence of future climate change scenarios on hydrology and bioenergy production. Determine the potential impact of landscape alteration due to fuel crop conversion on local precipitation and other weather variables.
- **Understand the impact of biofuel production on water quality to improve prediction and management.**
  - Develop field trials that generate near real-time data for identifying the impact of bioenergy crop production on water-quality parameters, and expand hydrological models to include these new data.
  - Link research and modeling on water quantity and quality with information on soil processes and crop growth to more accurately predict the effects of biomass management options.
- **Improve approaches to bioenergy feedstock management.**
  - Develop new approaches to agricultural and silvicultural land-use design and management practices that reduce runoff of sediments, nutrients, pesticides, or other inputs.
  - Develop integrated decision-making tools at farm, regional, watershed, state, and national levels by integrating data from appropriate spatial and temporal scales of water use, supply, and quality.

- Determine how site preparation, management, and harvesting strategies for crops and forestlands can be done to minimize erosion and sediment loss.

2.3. Biodiversity and Ecosystem Services

Previous sections discussed ecosystem services such as soil fertility and crop productivity, control of greenhouse gases, and water supply and contamination. Rural landscapes provide many other basic ecosystem services that will continue to be crucial to maintain and improve as the biofuel sector emerges. For instance, a diverse biofuel production system including native species could increase local biodiversity and provide suitable habitat for organisms such as wildlife and predatory or pollinating insects that are beneficial to agricultural and natural ecosystems.

Ecosystem biodiversity often has been associated with a broad range of services, and the idea that more diverse ecosystems sustain greater productivity and system stability is an appealing concept (Shennan 2008). However, the degree to which ecosystem biodiversity is impacted—for better or worse—by the inclusion of biofuel production into existing rural landscapes still needs to be understood to ensure not only sustainable production of biofuels but also food, fiber, and feed.

Research into the effects of integrating bioenergy production into U.S. agricultural systems provides an opportunity to rethink the structure and function of agricultural landscapes. Sustainable approaches to biofuel production may require diversified and highly integrated management systems to produce the mass of cellulosic feedstocks necessary while at the same time providing needed goods, services, and values from the same working landscapes (Cassman and Liska 2007). Current perennial feedstock management alternatives range from low-diversity systems using a single species (e.g., switchgrass and *Miscanthus*) that produce the greatest biomass per unit area (Schmer et al. 2008) to greater-diversity systems (e.g., mixed forest or grasslands) that may produce lower yields but provide increased ecosystem services (Tilman, Hill, and Lehman 2006; Wallace and Palmer 2007). Research will help understand how these management alternatives compare for a wide range of ecoregions and in conditions in which biofuel feedstocks are likely to be produced. Even in existing agricultural landscapes, few studies have sought to quantify the value of natural landscape components that support ecological services such as wildlife habitat maintenance (McComb, Bilsland, and Steiner 2005). Further research is necessary to value ecosystem services, even though many may not be amenable to monetization or even quantification (Mitchell, Vogel, and Sarath 2008). Quantified measures of ecosystem services will be easy to include in decision models. However, one goal for the investigations should be to generate results in a form amenable to decision making that does not rely on quantifying tradeoffs.

Ultimately, the capacity and feedstock flexibility of cellulosic biofuel refineries may be drivers of changes in landscape structure and therefore significant determinants of biodiversity and ecosystem services. If biorefineries are optimized for a single feedstock, this could tend to reduce landscape diversity and ecosystem services within the feedstock supply area. However, win-win scenarios could be envisioned in which integrated production and processing of multiple cellulosic feedstocks enhance ecosystem services. For example, research could help guide strategies that augment ecosystem services through such approaches as planting small amounts of perennial vegetation grown for cellulosic biomass and strategically located as parts of conservation or riparian buffers that also enhance water quality, pollination, and biocontrol. At larger scales, adding perennial crops could help protect critical habitat corridors.

The impacts on ecosystem services of biomass crops that may become invasive are uncertain. Research is needed to predict the potential impacts as well as to reduce risks.

Research Opportunities

- **Identify ecosystem goods, services, and values provided by biofuel feedstocks.**
  - Determine ecosystem services for different ecosystems where agricultural and forest feedstocks are likely to be produced. Ensure that the investigations are applied to diverse landscapes, including those dominated by unmanaged landscape components, and areas where food, feed, and fiber are primarily grown.
  - Explore the links among diversification of agricultural landscapes, resilience, and provision of ecosystem services to guide management.
  - Analyze the impacts of climate change scenarios on ecosystem services across a broad range of biophysical and ecological conditions.
- **Develop ways to increase ecosystem services.**
  - Develop quantitative models and decision tools to evaluate the service, including to monetize it where possible, and bundle ecosystem services to help identify management tradeoffs and synergies, guide more sustainable production decisions, and decrease unintended consequences.
  - Develop harvesting techniques that gather feedstock from timber stands with minimal impact on ecosystem resilience and services.
  - Investigate the potential invasive or gene transfer consequences of introducing new or transgenic bioenergy feedstocks. Develop options to reduce any risks that introduction of these into production systems may present.

2.4. Integrated Landscape Ecology and Feedstock Production Analysis

By its very nature, bioenergy sustainability will require a systems perspective of landscapes across scales—from fields and farms to watersheds and larger regions. Landscape ecology is the study of relationships between spatial patterns and ecological processes for a multitude of scales and organizational levels.

Regional Perspective

To date, bioenergy research has emphasized investigations at small-plot, farm, or field scales and, to some extent, very large scales such as political, national, and global scales. There is a gap, however, in the middle scales, from watersheds to larger regional scales, that may be the most relevant to environmental issues in general and sustainability issues in particular (Robertson et al. 2007). In many cases, current models have not been evaluated for their suitability across varying ecoregions and at different spatial scales of resolution. Furthermore, few field studies have been conducted into the effects of bioenergy feedstock production on watershed quality for ecoregions where feedstocks could be sustainably produced. Without field-based research and the validation of model results, these deficiencies could pose major challenges to the design of biofuel production systems that actually are sustainable. The chief barriers are the lack of knowledge regarding how different processes interact at different scales of resolution, validated model results to interpret impacts across broad ecoregions, and decision tools to direct the development of sustainable management practices and systems. Interdisciplinary research teams involving scientists from the agricultural, forestry, ecological, socioeconomic, and information systems communities will be required to fill such knowledge and technology gaps and provide integrated solutions that effectively target specific components at the appropriate spatial scales. Principles and processes for how human and natural resource systems interact need to be better understood, especially in view of regional landscapes that contain a mosaic of farming and forestry activities, natural areas, and communities.

Model Integration

Improved models and analytical frameworks are needed that integrate biophysical and ecological processes at regional scales, together with economic and other aspects of human behavior. Mechanistic models of crop growth and yield, carbon sequestration and greenhouse gas fluxes, water quality and hydrology, and biodiversity benefits have been developed at plant and field to small regional scales. Economic models have been developed to capture the impacts of landowner choices with respect to what to grow and how to grow it, including how changes in quality of the natural resources feedstock supply affect prices (Johansson, Peters, and House 2007). Biophysical and economic models have just begun to be combined for analyzing the environmental and economic impacts of technology and policy alternatives and to optimize multiple management objectives (Whittaker et al. 2007). Such integrated analyses are needed to ensure the sustainable use of agricultural landscapes as implementation details and potential tradeoffs will differ across regions. If not fully integrated, these tools used alone may not capture important feedbacks and interactions (Antle and Capalbo 2002). Additionally, the continued development of datasets is necessary to validate model results at regional and other scales (Sadler et al. 2008; Steiner et al. 2008), to ensure the sustainable use of agricultural landscapes as implementation details and potential tradeoffs will differ across regions.

Research Opportunities

- **Investigate landscape ecology at regional scales to understand the relationships among diverse processes.**
  - Develop analytical frameworks for regional-scale ecological models. Link these models with biophysical and economic models to understand how key

aspects of bioenergy production affect the multifunctional roles of agricultural and forest landscapes.

- Develop regional models that enable the evaluation of management options for climate change scenarios.

3. Economic Dimensions of Biofuel Sustainability

Economic research can help in determining the direct cost competitiveness of cellulosic biofuels with competing sources of transportation fuels. However, the production of biofuels has direct implications for a wide variety of ancillary environmental and social consequences. Expanded economic research will be critical for better understanding the connections among these ancillary impacts and will help support policies leading to development of a biomass sector that creates incentives consistent with society's values.

3.1. Economic and Market Impacts

Several potential sources of cellulosic feedstocks include agricultural crop and forestry residues, perennial grasses, and short-rotation woody crops. An active area of economic research is to determine the mix of cellulosic feedstocks likely to be competitive in different regions, the spatial pattern of land-use changes these feedstocks will induce, and their implications for crop production and management and for commodity and food prices. Current economic research suggests the possibility of considerable spatial heterogeneity in optimal choice among different feedstock crops, and often a mix of cellulosic feedstocks is likely to be selected. Yields of cellulosic feedstocks are critical determinants of their economic viability (Perrin et al. 2008). Furthermore, to envision a viable biobased energy system, bioenergy crops must compete successfully with traditional food, feed, and fiber crops and with conventional petroleum fuel sources. Farmers will produce cellulosic feedstock crops only if they can receive an economic return at least equivalent to returns from the most profitable alternative crops.

Current economic models of agricultural production can estimate national and regional feedstock production; the role of livestock production; and input demands such as land, fertilizers, and tillage and other production practices. These models also can predict the impacts of increasing biofuel production on commodity and food prices. Although existing models can predict aggregate land-use change, more precise estimates—particularly at smaller scales—will require additional data and research.

A broad assessment of economic impacts requires looking at both the supply side and demand side of markets. Much of current economics research is focused on the supply-side implications of ethanol production (e.g., for agricultural producers, land use, and crop production). A broader assessment also requires consideration of the demand side to determine how consumers' preferences influence outcomes. For example, the demand for biofuels will depend in part on the availability of flex-fuel vehicles, the cost and availability of biofuels and blended fuels, and market prices for gasoline. Economic models need to incorporate the determinants of demand for biofuels under various scenarios of substitutability of biofuels and oil to assess the impact on prices and biofuel use.

Finally, economic analysis of biofuels should consider the implications of biofuel production, prices, and resource use within the global market. For example, the potential for Brazil to substantially expand production of sugarcane ethanol could influence the competitiveness of cellulosic biofuels in the United States. Global economy-wide models examine commodity production at country and subcountry scales and provide insight into direct and indirect land-use impacts of U.S. and international biofuel production. The driving forces behind land-use change in many parts of the world, however, are linked to political, biophysical, cultural, infrastructure, land-tenure, and social factors in addition to commodity markets. Research will enable modeling of such diverse factors.

External benefits and costs of biofuels, such as environmental consequences, are unlikely to be included adequately (if at all) in private-sector decisions about biofuel consumption and production in the absence of government policy based on sound science. Decision models need components to represent the effects of choices such as feedstock crops, tillage practices, and nutrient applications as well as the impact of agricultural and forest residue removal on soil quality.

Economic analysis can contribute to the design of policies that can address sustainability concerns at least cost to society. Moreover, economic analysis also is needed to examine the social costs and benefits of existing biofuel policies such as mandates, tax credits, and import tariffs. For example, the extent to which biofuel mandates reduce gasoline consumption and mitigate climate change depends on a number of parameters that capture human behavior. These include the responsiveness of ethanol and gasoline supply to prices, the extent of substitutability between ethanol and gasoline, and the responsiveness of fuel demand to higher fuel prices.

3.2. Forestry Economics and Land Use

The development of a cellulosic biofuel sector raises a number of questions regarding the future structure of forests and the flow of multiple benefits from these systems. New facilities are just beginning to compete for raw materials in some areas. Although new facilities are being constructed where these materials appear plentiful, not all standing biomass can be considered “available” for timber harvest. Rather, harvest choices and the supply of forest biomass depend on the preferences of private landowners who control the vast majority of commercial timberland in the United States.

Research is needed to ascertain the extent of the potential supply in all forest-producing regions. Research also is needed to address landowner preferences for timber-based revenue versus nontimber amenity values of forests and the implications for aggregate timber supply. In addition, because forest biomass already is used in so many other production processes, understanding the full structure of supply that addresses the complementarities and substitutability of fuel stocks with current production of sawlogs, pulpwood, poles, and other products will be important. This is fundamental to understanding the potential coevolution of all wood-using sectors. Another important element is the competition of agricultural and forest-based production processes for biofuels and the potential for land-use change in response to changing returns from agricultural and forestry products. Also, both forest and agricultural land are competing with exurban development in many regions, adding another dimension to land-use issues associated with biofuel sustainability.

3.3. Integration of Economic and Biophysical Feedstock Modeling

Research underlying the development of models that fully represent the economics of biofuels requires an interdisciplinary approach. It should integrate biophysical models of feedstock production involving plant, soil, and other ecosystem processes with economic models of production and human behavior. These integrated models should reflect soil carbon biosequestration and take into account the spatially variable nature of agricultural production and environmental quality. Some options, such as selecting perennial crops and placing biorefineries, imply multiyear consequences. New research should represent both economic and environmental effects at regional scales that best capture sustainability issues. Although current economic models can indicate changes in the type and location of production, less is known about the direct impacts of changes on soil and air quality, water use and quality, wildlife habitat and biodiversity, and other environmental considerations.

Such integrated modeling also can play an important role in helping direct biofuel production toward a sustainable future by providing estimates of the social costs and benefits of various policies. Integrated modeling can inform decision makers about the design of alternative policies that consider incentives for reducing greenhouse gas emissions, water-quality degradation, and loss of biodiversity.

Global information on the availability and productivity of land for feedstock production is needed to estimate the potential supply of cellulosic feedstocks in competition with other uses. In particular, identifying the amount of underutilized rural land available for expanding crop production around the world vis-a-vis existing forests, nature reserves, urban areas, and current harvested areas is necessary to determine the implications of indirect land-use changes on greenhouse gas emissions in other countries.

3.4. Life Cycle Analysis

To understand the sustainability of a biofuel, knowing the effects of production and consumption throughout the entire biofuel system is critical. To model the entire system, defining system boundaries is important in including as many relevant factors as possible. Life cycle analysis (LCA) is one of the methods used to conduct these kinds of assessments. This particular approach is especially important to the sustainability of biofuels; it has been addressed explicitly in legislation and will be used by the U.S. Environmental Protection Agency to aid in sustainability assessments. The construction of LCAs for multiple feedstock and conversion technologies of proposed candidates for regionally significant production should include well-to-wheel approximations of net energy production (Schmer et al. 2008). Other considerations needed are mass balance analysis of irrigation water and precipitation, land use, nutrients, and agrichemicals associated with prospective feedstocks and conversion technologies.

As traditionally defined and practiced, using LCA to capture some of a system's critical complexity is difficult. Substitutions among existing technologies in response to relative price changes and technological changes that increase efficiency are not captured by current LCA. It also does not analyze indirect land use, is not dynamic, and does not easily accommodate multiple changes simultaneously.

However, performing LCA is important for the evaluation of biofuel sustainability. These analyses should be conducted at a variety of geographic scales. For instance, additional research is needed to determine the net energy requirements of larger-scale feedstock cultivation and biofuel processing facilities to better define the efficiencies possible in cellulosic biofuel production systems. Assumptions involved in LCA should be transparent so that fair comparisons can be made across different biofuel technologies. For example, some biofuel technologies may be more carbon saving while others may reduce oil imports. Direct and transparent analyses enable an assessment of these kinds of tradeoffs. Sensitivity analyses should be conducted to explore alternate assumptions and parameters, with uncertainties in underlying processes and parameters clearly set forth. LCA models should accommodate risk analysis and flexible representations of various input parameters. Furthermore, a variety of potential users would benefit from user-friendly models.

Comparisons of the greenhouse gas results from LCAs can be difficult because biofuel production systems tend to be complex, and the scope, parameter values, methodologies, and assumptions about energy inputs or credits (e.g., the potential for electricity cogeneration) and other factors tend to be uniquely defined for each study (Liska and Cassman 2008; Dale et al. 2008). To make LCA useful for these comparisons, approaches should be standardized (Wallace and Mitchell 2009). LCA modelers should determine how to set standards and practices such as similar treatment of a common set of variables.

3.5. Emissions from Land-Use Change

A major limitation to current LCA models is the inability to measure and account for greenhouse gas emissions from land-use change. Methods are needed to rapidly measure greenhouse gas emissions across variable landscapes so that the effects of land-use redirection to biofuel production can be determined. These should include emissions from the clearing of forests, grasslands, and other natural ecosystems to produce biofuels or other agricultural crops displaced by biofuels (e.g., Fargione et al. 2008). LCA models should be developed that assume realistic soil management practices and accepted technologies. These technologies include the use of conservation tillage or low-disturbance systems and the retention of proper amounts of crop residue on the soil surface so that impacts on existing levels of soil organic carbon are minimized even after several years of cropping (Follett et al. 2009).

Realistically assessing the impacts of biofuel production in the United States based on land-use choices elsewhere is especially difficult because potential land-use change is influenced by many different factors, including the expansion of roads and infrastructure into undeveloped lands for other purposes, changes in the values of agricultural and wood products, developing technologies, and sovereign choices. Drivers of land-use change are not single actions but complex interactions among cultural, economic, technological, political, and biophysical forces (Dale et al. 2008).

Methodologies for quantifying changes in land use that are attributable to biofuel production are still in the early stages of development.

3.6. Economic Risks and Uncertainty

The uncertainty of future events such as severe weather, climate change, or dramatic changes in oil prices can have important consequences for decisions spanning long periods of time. Assessing the level, source, type, and location of risk associated with various uncertainties is an important consideration in economic research. At the level of farm decisions, annual crops provide some flexibility not present in perennial biofuel crops. Decisions by farmers are sensitive to expectations regarding biorefinery investments and operations, future improvements in crop varieties, petroleum prices, and many other multiyear changes. Production of cellulosic feedstocks imposes new risks on producers and refiners because it can involve decision making and contractual commitments over many years. Uncertain market prices for energy crops and lack of other market outlets for those crops can make energy-crop profits dependent on uncertain or volatile oil prices and on the location of biorefineries. The uncertainty caused by possible rapid innovations leading to new, genetically superior varieties of energy crops or improvements in conversion technologies also could influence investment decisions.

These multiyear decisions are common in economic analysis, for example, option theory and decision theory. Accommodating risk and uncertainty in much of the current biofuel analysis, however, will require research. Properly representing risk will be particularly important if decisions are to be made regarding potential governmental policies. For sound public policy designed to support a sustainable biofuel industry, research is needed on the implications of alternative models of contracting for feedstock, providing crop insurance, and other risk-mitigating and government-based safety nets.

New biofuel crops may provide new sources of revenue and enhanced job prospects for selected rural areas. Biorefining may provide further economic opportunities and stimulate growth. Economic opportunities for farm and rural communities need to be considered in the context of farm and off-farm economics and finance. The extent to which rural communities will capture these economic benefits is still unknown. Economic modeling would help predict, for example, how different parties might capture the profit and bear the risk in the biofuel value chain and estimate the multiplier effect that forecasts job growth.

Research Opportunities

Economic modeling applied to sustainable biofuel production is still nascent. It is driven by the need to supply information to a variety of decisions as well as to serve as input for analysis by other experts. Some needs include the following:

- **Estimate the quantity and cost of biofuel production.**
  - Develop regional and aggregated biofuel supply models that integrate the diversity of energy feedstocks, growing conditions, ecosystem services, and economic parameters.

- Develop scenarios of patterns of biomass crop selection and cultivation at national, regional, and local levels. Provide these scenarios to analysts and decision makers in related policy areas such as climate change, international trade, water quality and demand, and rural development.
- Model and analyze the economic implications of biofuel production, prices, and resource use within the global market. Consider international markets and trade in the production of biofuels.
- Expand supply model capability to include analysis of climate change scenarios that could affect long-term growing conditions.

■ **Evaluate the amount of noncropland available in the United States and other parts of the world.**

- Assess and quantify competing land use and examine forces that cause indirect land-use effects.
- Investigate factors (economic and noneconomic) that influence the potential conversion of different land uses or covers to feedstock production.
- Use information from ecological studies and models to assess the availability and value of land, water, and other natural resources.

■ **Analyze ancillary benefits and disbenefits of biofuel production through life cycle analysis.**

- Expand life cycle analysis to capture critical processes and parameters that will enable the examination of well-to-wheel biofuel production. Provide ways to develop standard assumptions so comparisons of different LCAs can be more transparent and accomplished easier.
- Quantify the factors responsible for land-use change to assess the carbon fluxes appropriately attributable to the establishment of biofuel cropping systems elsewhere. Incorporate indirect land-use effects as appropriate into LCA models.

■ **Develop decision tools to enable encouragement of the adoption of onfarm practices to meet environmental objectives.**

- Analyze the economic effects of policy options that provide economic incentive mechanisms and encourage compliance with environmental objectives.

■ **Provide information on future infrastructure requirements.**

- Analyze demand for flex-fuel vehicles, filling stations, and ethanol transportation.

4. Social Dimensions of Biofuel Sustainability

Previous sections of this report discussed environmental and economic dimensions of cellulosic biofuels and related research needs. This section outlines the science agenda required to understand the social and technological changes needed to achieve sustainable biofuels, including their implications for farmers, foresters, rural communities, and other stakeholders. The biofuel sector cannot develop sustainably without an understanding of and effective response to stakeholder values, choices, behaviors, and reactions, along with careful consideration of the social structures and policies influencing that development. Research and engagement in this arena will provide policy and decision makers with information needed to support decisions at individual, community, and national scales.

4.1. Understanding Stakeholder Needs and Motivations

Everyone has a stake in national energy security and in sustainable biofuel development, but farmers and foresters; rural community decision makers; the biofuel industries; and local, regional, and national policy makers will play pivotal roles in achieving a sustainable future. A wide range of motivations drives stakeholder values, choices, and behaviors: price signals, resource and equipment needs, infrastructure requirements, environmental protections, number and quality of jobs, lifestyle changes, economic multipliers, and policy incentives. Understanding how stakeholders view, evaluate, and make choices about potential opportunities and risks of biomass and biofuel development is essential to designing and managing systems that capitalize on the opportunities while avoiding or mitigating unintended adverse consequences.

Sustainable feedstock production and biofuel development have the potential to fundamentally alter the management choices and practices of farmers and foresters, changing agricultural and forestry landscapes as well as rural communities. Growing feedstocks for biofuels presents new job opportunities in biomass production, transport and storage, biofuel processing, and ancillary services and industries, but these changes are likely to place increased demands on essential resources and systems needed for food production, power supplies, transportation, and water quality and quantity. The extent of change in rural demographics and development, as well as the effects on farmers, foresters, rural communities, and other stakeholders, will depend on many things, including land tenure, individual and regional land-use decisions, workforce development, community capacity, biorefinery ownership, biomass processing choices, and whole systems designs.

4.2. Building on Lessons Learned from Biofuel Production at Home and Abroad

The nation has nearly two decades of experience with grain-based biofuels. Corn ethanol and soy diesel, which have contributed significantly as substitutes and additives for fossil fuels, have brought us to our current threshold of cellulosics. Yet, intensification of grain production for biofuels has raised a number of concerns relevant to long-term sustainability including resource competition, soil and water degradation, wildlife habitat and conservation disturbance, gulf hypoxia, disruption in the livestock industries, and escalating food prices. Learning from the U.S. experience with grain-based biofuels like corn ethanol and soy diesel will be important to avoiding past mistakes that could threaten the successful expansion of cellulosic biomass and biofuel production.

Only through a nuanced understanding of the social dynamics surrounding biofuel production will producers, policy makers, and community decision makers be able to design systems that prevent or mitigate unintended adverse consequences. This will include understanding the relative social merits and shortcomings of various biomass alternatives at different spatial and temporal scales, understanding the social advantages and disadvantages of biomass monocultures and polycultures and deliberating the tradeoffs, and understanding the relative social benefits and risks of diversified biofuel production enterprises. Inherent in all this is evaluating or examining how the many stakeholders identify, value, and weigh the social costs and benefits, negotiate the myriad tradeoffs that will be required, and respond to the consequences.

Just as the lessons learned in the U.S. experience with grain-based biofuels are crucial to future planning and development, so too are the lessons learned by other biofuel efforts in Europe, South America, and elsewhere. Insights from international experiences will provide a broader view of numerous issues including interconnections among global resource inventories, competition, and responses; potential effects of different policy and incentive options; stakeholder acceptance of new technologies; environmental risks and protections; and development of effective practices in agriculture, forestry, community planning, and facility siting.

4.3. Understanding the Social Effects of Scale and Complexity for Biofuel System Design

Farms, woodlots, forests, and communities vary markedly by size, complexity, climate, geography, resource endowments, and human capital. Therefore, research and design of cellulosic biomass production need to reflect this diversity as well as the values and capacities of rural communities, biofuel and agricultural industries, and other stakeholders. Analysis and understanding must encompass multiple scales and complexities—from individual farms and forests to whole communities and ecosystems—so science can inform decision making and design at local, regional, national, and global levels.

The effects of scale are not limited to cellulosic biomass production but extend also to biofuel development and systems design. Scale and ownership patterns will influence the design and siting of biofuel facilities. The scale of facilities will affect and be affected by industry concentration, community capacity, infrastructure support, transportation and storage costs, workforce potential, and income generation. The environmental outcomes that differ by feedstock and processing facility scale and complexity will influence public perceptions and support. Research is needed to identify biorefining systems and enterprise structures that optimize benefits and reduce undesirable consequences for biomass producers and communities and society at large. The implications of ownership and scale for cellulosic feedstock production, conversion technologies, and biorefining systems require examination, as do the development options they permit.

4.4. Understanding Social Dynamics, Human Choices, Risk Management, and Incentives

The pursuit of sustainable biofuel production will entail many decisions, negotiations, compromises, and tradeoffs on the part of feedstock producers, rural communities, biofuel industries, and society generally. Agricultural and forestry biomass providers will make feedstock choices constrained by various geographic and climatic conditions, resource availability, equipment requirements, establishment costs in time and investment, labor demands, and their own technical and financial capabilities. Land tenure constraints, risk management options, and enterprise goals also will influence choices and management practices of feedstock producers. Their decisions and behaviors will depend on whether they own or rent land and, if they rent, whether their landlord is a family member, a neighbor, a rural community member, an urban absentee owner, or a corporation. Other factors influencing producer decisions are whether they have authority to make short- and long-range decisions on land use, resource management, cropping choices, and equipment investments; their level of indebtedness; the risk management tools at their disposal; and the types and duration of contracts, subsidies, and conservation programs to which they have committed. Likewise, their decisions and practices will be shaped by the goals of their farming and forestry enterprises. A goal to support a family through farming or to bequeath land to a new generation of farmers will influence decisions and behaviors differently from a goal to sell the land, resources, or enterprise to developers. Choices made on farm or forest enterprises can be driven more by short-term profitability than long-term viability, or by some balance of both. Decisions of biomass producers will depend on the unique conditions defining each scenario.

The decisions and decision-making processes of communities are similarly complex. Rural community members, as individuals and in aggregate, evaluate options and make development decisions based on available resources and their capacity and willingness to support, finance, and invest in new futures. They determine their level of infrastructure needs and support and make investments through zoning, taxes, incentives, and policy in an effort to attract business; support production; generate revenue, jobs, and income; and maintain viability. Workforce development needs and capacities are central to their planning as they assess current capacities, examine prospects for growth or development, and mobilize their efforts. Resource inventories provide a window on the extent of resource competition against which alternative uses must be weighed and difficult options negotiated. The development and quality-of-life goals of communities and their constituent members will differentially shape the decisions and actions they make to pursue cellulosic feedstock and biofuel development.

Feedstock providers and rural communities are not the only stakeholders making decisions in this arena, of course. Biofuel industries are actively engaged in feedstock inventories and assessments of resource availability. They evaluate infrastructure needs and availability and consider flexible conversion technologies and facility siting accordingly. Their decisions are constrained by the sufficiency of these resources, as well as by financial, economic, and political considerations. Their ability to leverage resources, negotiate contracts, and influence community decision makers, as well as their capacity to handle logistics and operate processing competitively, all shape the kinds of decisions and investments that industry makes.

Sustainable biofuel development is motivated by at least five larger societal goals: improved farm and forest economies and producer well-being; rural economic development; global climate change mitigation; energy security; and national security. At times these goals may not seem complementary or compatible. Understanding whether and how different stakeholders can reach consensus about these goals and the paths to achieve them is an essential focus of the social sciences and the decision and risk management sciences, as well as the planning and design disciplines. It will be important to identify societal outcomes at a variety of scales and for various scenarios, understand economic and political constraints, assess the commitment of different sectors of society, and sort out the values, compromises, negotiations, and tradeoffs that will be necessary to attain these outcomes. Research and understanding of these social processes can provide policy and decision makers at all levels with information essential to policy development and negotiation, incentive creation and evaluation, and design of support mechanisms and structures to best serve larger societal goals.

Finally, information access is another critical issue. Stakeholders of all kinds—be they feedstock providers, community planners, industry professionals, or national policy makers—will need to find information supported by environmental, economic, and social science research to identify the many alternatives, evaluate options, weigh likely outcomes, and make decisions. A diverse portfolio of research, decision aids, education, communication tools, and outreach and extension activities will be needed to inform and support their decisions. These are among the many social science challenges that will require future investment by the research and development communities committed to achieving sustainable biofuel futures.

Research, Education, and Extension Opportunities

Addressing the challenges underlying the human and social dimensions of cellulosic biomass and biofuel development must be a part of any research and outreach program focused on sustainability. The issues raised in this section are concisely captured in the following list of investment opportunities. Although these opportunities are framed from a social science perspective, their solution will require the collaborative efforts of ecologists, biological and physical scientists, systems design engineers, and economists alongside sociologists, geographers, agricultural historians, family and consumer scientists, agricultural educators and communicators, and extension professionals.

Understanding Stakeholder Needs and Motivations

- Identify incentives and impediments to individual farmer and forest landowner decisions to grow energy and alternative crops.
- Identify and understand land tenure characteristics, crop and product attributes, capital and equipment needs, management practices, labor demands, and technical capacities that influence adoption of cellulosic biomass crops by farmers and foresters.
- Identify and understand market characteristics and financial and community support programs that influence adoption of cellulosic biomass crops by farmers and foresters and biofuel facilities by communities and industry.
- Develop specialized risk management tools to assist feedstock providers and biorefining facilities. Identify barriers to new investment and development and commercialization of new products.
- Assess rural infrastructure and workforce development needs and opportunities.
- Analyze the social processes, structures, and institutional arrangements underlying community capacity, vulnerability, and resiliency.
- Investigate and design strategies to create, increase, and retain value from cellulosic biomass and biofuel development for agricultural producers, private forest landowners, and rural communities.

Building on Lessons Learned from Biofuel Production at Home and Abroad

- Conduct comparative, historical, and international research to evaluate the experience with U.S. production of grain-based biofuels and other countries' bioenergy production.

Understanding the Social Effects of Scale and Complexity for Biofuel System Design

- Develop tools, metrics, and design criteria to assess social, economic, and environmental sustainability of cellulosic feedstock and biofuel development at local, regional, national, and global scales.
- Conduct spatial and temporal analyses of farmer and forester adoption, community support and outcomes, industry experience, and societal responses to cellulosic feedstock and biofuel development.
- Develop scale-neutral and scale-sensitive research and technologies to compare differential consequences of variously scaled cellulosic biomass and biofuel production systems and assess the outcome of large industrial-scale, regionally based, and local decentralized energy systems.

Understanding Social Dynamics, Human Choices, Risk Management, and Incentives

- Analyze stakeholder values, evaluations, actions, and responses regarding alternative biofuel crop options, different ownership models, infrastructure requirements, employment options, and environmental concerns to provide the science foundation to inform decision making at all levels.

- Evaluate a range of rural community effects including changes in water use and demand, management of biorefinery wastes, impacts on property value, reactions to increased ownership concentration, fewer farms, and less control of biofuel production systems to provide the science foundation to inform local decision making as well as local, regional, and federal policy making.
- Conduct modeling and analysis to evaluate the efficacy of existing and proposed incentives for cellulosic biofuel development; examine their effects on rural communities; and predict impacts of these options on biomass production, biorefining capacity, bioenergy industry structure, trade, and international markets.
- Assess potential approaches for developing human capital in anticipation of changing labor requirements.
- Identify and evaluate incentives, investments, and formal or informal educational needs required to nurture biomass producers.
- Develop appropriate education and outreach programs that inform the next generation of cellulosic feedstock producers, as well as biofuel workers and consumers, and provide information to communities for sustainable biofuel development.

5. Summary

The joint USDA-DOE Sustainability of Biofuels Workshop, held October 28–29, 2008, stimulated an interactive discussion among a wide range of experts on the state of the science and research needed to establish sustainable production and utilization of cellulosic biofuels. This report summarizes that discussion and presents a series of new and critically important areas of research. Interdisciplinary teams involving scientists from the agricultural, ecological, socioeconomic, and information system communities will be required to fill knowledge and technology gaps and provide integrated solutions that effectively target specific challenges. This research, however, must maintain a holistic view of the entire biofuel production system and its socioecological impacts. DOE, USDA, and other federal agencies now have a unique opportunity to use these recommendations to develop an integrated research agenda that addresses the environmental, economic, and social dimensions of cellulosic biofuels across multiple scales and ensures that this emerging industry grows sustainably.

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Appendix B. List of Participants

Sustainability of Biofuels Workshop

State of the Science and Future Directions

A Workshop Jointly Sponsored by the
U.S. Department of Energy and the U.S. Department of Agriculture
October 28–29, 2008
Bethesda Marriott
in Bethesda, Maryland

Opening Plenary Session Presentations by Senior Federal Agency Officials

Gale Buchanan
Under Secretary for Research, Education, and Economics
U.S. Department of Agriculture

Raymond Orbach
Under Secretary for Science
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Anna Palmisano
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