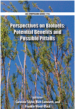

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Perspectives on Biofuels: Potential Benefits and Possible Pitfalls

EDITED BY
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Frankie Wood-Black

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In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
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Before agreeing to publish a book, the proposed table of contents is reviewed for appropriate and comprehensive coverage and for interest to the audience. Some papers may be excluded to better focus the book; others may be added to provide comprehensiveness. When appropriate, overview or introductory chapters are added. Drafts of chapters are peer-reviewed prior to final acceptance or rejection, and manuscripts are prepared in camera-ready format.

As a rule, only original research papers and original review papers are included in the volumes. Verbatim reproductions of previous published papers are not accepted.

ACS Books Department

Dedication

To our editor, Tim Marney, for never losing hope,

and to Maggie Taylor, who had to go before it finished.

Editors' Biographies

Caroline Taylor

Caroline Taylor is a Senior Bioenergy Analysis Fellow at the Energy Biosciences Institute at the University of California, Berkeley. She holds Bachelors degrees in Classics and Chemistry from the University of California at Irvine, a Doctorate in Chemistry from the University of Chicago, was a post-doctoral fellow at Cornell University and has held a number of visiting appointments. She joined EBI from the faculty of MTU's College of Sciences and Arts to co-found EBI's integrative Bioenergy Analysis Team, where she assesses the viability of emerging plant-based solutions for addressing global energy needs sustainably, participates in international collaborations on regionally-specific bioenergy/biofuels scenarios, and engages with a range of stakeholders from engineers to policy makers.

Rich Lomneth

Rich Lomneth is currently an associate professor and chair of the Department of Chemistry at the University of Nebraska at Omaha (UNO), where he has been since 1992. He received his B.S. in Chemical Engineering from Virginia Tech and his Ph.D. in Biochemistry from the University of Cincinnati College of Medicine. After graduation from Virginia Tech he was a research chemical engineer for Procter & Gamble, working in the Foods Division. He has been involved in the programing and writing of policy statements for ACS and is the Councilor for the Omaha Section of the ACS and a member of the ACS Committee on Environmental Improvement.

Frankie Wood-Black

Frankie Wood-Black has been in the petroleum and chemical industry for over 23 years with work experience in technical management, laboratory operations, environmental science and compliance, finance, and professional development. She has a B.S. from the University of Central Oklahoma and a Ph.D from Oklahoma State, both in Physics, and an MBA from Regis University. Dr. Wood-Black's work experience has primarily been focused around the refining and downstream operations. Prior to joining Trihydro she served as the Director of Consent Decree Compliance for ConocoPhillips, which focused on environmental air compliance for refining operations.

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
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Chapter 1

Putting Biofuels into Context Beyond Biofuels Chemistry—Context, Issues, and Broader Perspectives Important to the Technical Audience

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Today, fossil fuels dominate the worldwide energy mix. Combining the finite supply of fossil fuels with their adverse environmental impact and the uneven worldwide distribution causes political and economic tensions. Biofuels can improve the current energy portfolio since they are renewable resources grown domestically thereby offering potential economic, environmental and security benefits. The role of biofuels as a liquid fuel replacement is nascent, but projected to grow significantly in the coming years as chemists and chemical engineers contribute to solving technical problems in the use of lignocellulosic feedstocks. To insure we take the wisest approach during biofuel development, chemists and engineers in their roles as managers and policy makers need to have a broad perspective of the impacts of biofuel production so they are able to consider the long-term impacts of biofuel development on the economy, environment and society.

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The Energy Portfolio and Concerns of Fossil Fuels

A variety of abundant, sustainable, inexpensive and secure energy sources which cause minimal damage to the environment while also being safe to use and produce represent the ideal energy portfolio for today and the future. In contrast, the present energy landscape is dominated by non-renewable fossil fuels, mainly petroleum, natural gas and coal. Global primary energy consumption in 2010 was 500EJ (479 quads), of which 87% came from fossil sources (39% petroleum) (*1*). Energy consumption in the US during 2010 was nearly 100 quads (quadrillion British Thermal Units) with petroleum being the largest contributor accounting for about 36 quads. Overall, fossil fuels supplied about 83% of the total US energy demand (*2*).

Fossil fuels have been relatively inexpensive and have a high energy density which has lead to their widespread adoption throughout the world. However, the fossil fuels have well recognized drawbacks. Fossil fuels by their very nature are not renewable on a time scale useful to humans. Supplies are still relatively abundant, but the supply varies greatly among geographic region. The U.S. has already passed its peak production of petroleum and other nations may be reaching peak production soon (*3*). According to estimates by BP, the reserves to production ratio for the U.S. is slightly less than 11 years (*1*). This does not mean that petroleum will be unavailable, but it does mean that as supplies decrease the costs of using petroleum will continue to increase, potentially dramatically.

Environmental damage is another large concern related to fossil fuels. Major spills such as those caused by the Exxon Valdez running aground in the Prince William Sound or the explosion of the Deepwater Horizon drilling platform in the Gulf of Mexico dominated headlines for months, but are relatively rare. However, smaller discharges are relatively common. It has been estimated that the annual anthropogenic release of petroleum into North American waters was about 100,000 kilotonnes during the period 1990-1999, with the majority of that coming during the consumption of fuel (*4*). Contamination of the land and water caused by drilling and transport of petroleum is also a concern. Mining of coal also damages the environment, particularly in areas where it is strip mined. The mining affects wildlife habitat and tailings from mines have contaminated both surrounding water and land. Even natural gas extraction is facing environmental review as the U.S. Environmental Protections Agency begins to examine potential hazards to groundwater from the use of agents to free natural gas from underground reserves (*5*).

While serious, these environmental issues themselves are unlikely to significantly hinder the continued use of fossil fuels. Larger concerns surround the actual combustion of fossil fuels, which releases previously-sequestered carbon to the atmosphere. Combustion of petroleum in the form of gasoline contributes to high levels of nitrogen oxides in the air, and previous use of lead-based fuel additives resulted in widespread lead contamination. Combustion of coal creates large amounts of sulfur dioxide and nitrogen oxides, which can be limited to a certain degree by treating the effluent gas. Despite improvements, the cost of sulfur dioxide, nitrogen oxides and particulate matter emissions from coal-fired power plants in the U.S. has been estimated to be around $62 billion (*6*). An additional concern is the release of heavy metals such as mercury, which has resulted in contamination of waterways and has moved up the food chain as it bioaccumulates in the form of organomercury compounds. Currently the largest concern is the production of greenhouse gases during combustion which are readily acknowledged to be increasing global temperatures (*7*). Climate change is the worldwide incentive for decreasing fossil fuel consumption. In the U.S., as elsewhere, another powerful driver comes from the added incentives of making energy resources more secure by producing energy domestically, supporting a decrease in our dependence on fossil fuels, and petroleum in particular.

Vast quantities of petroleum are traded globally. Of the 4032 million tonnes of oil consumed in 2010, 66% was imported, most to the U.S. and E.U. (21 and 22%, respectively) (*1*). The U.S. now imports about half of the petroleum it uses (*8*). It is well recognized that this creates both economic and security constraints on the importing country. Although Canada is the largest supplier of petroleum to the U.S., for example, significant amounts of oil come from countries in politically less stable regions of the world and/or from countries with which the U.S. does not have as strong political ties. The strategic concerns place a burden on military spending and deployment which creates additional economic costs on petroleum which are not directly seen by consumers.

Introduction of Renewable Fuels

Against this background, it is clear the U.S. and the rest of the world need to develop renewable energy resources to take the place of fossil fuels. “Global Challenges/Chemistry Solutions” produced by the American Chemical Society describes a “perfect storm” of conditions to spur the development of alternatives to fossil fuels: increasing petroleum prices, climate change concerns, national security and potential oil shortages (*9*). Some energy sources are readily available while some could take decades to fully implement in a cost-effective fashion. A variety of energy sources is necessary to best match the different applications and provide extra security to guard against the effects of the scarcity of one fuel type. Moreover, no one energy source will be optimal in all regions.

Each new energy system requires change to integrate it into our daily use, including construction of infrastructure to support it. Progress has been made in renewable electricity generation from wind and sun, and in some areas geothermal energy systems are being used to generate electricity. Biofuels are another potential renewable resource to replace a portion of our fossil fuel use. First generation renewable liquid fuels for transportation have focused on the production of bio-ethanol from starch or sugar and biodiesel from oil seed crops; next generation, or advanced, biofuels are being developed from grasses, woods, and residues, and algae. In addition to biofuels, many people have proposed replacing gasoline used for transportation with compressed natural gas, hydrogen or electricity stored in batteries. A small number of vehicles currently use compressed natural gas and a few major automobile manufacturers are beginning to offer electric vehicles for consumers. Market penetration of any of these technologies is likely to be very gradual, given costs and the lack of widespread infrastructure. In the near term, and for several sectors, liquid transportation fuels will continue to dominate.

Biofuel demand will continue to grow as at least a partial replacement for petroleum-based liquid fuels (see figure 1). Although most experts agree corn-based bioethanol and soy based biodiesel production as practiced in the U.S. are not sustainable, they serve as first generation fuels. Next generation feedstocks are emerging in response. Lignoellulosic materials are viewed as a long term sustainable feedstock for production of large amounts of ethanol other alcohol fuels, and advanced drop-in fuels. The long term feedstocks for renewable bio-based diesel are not as certain, but algae hold great promise. Chemists and chemical engineers will play a crucial role in overcoming technical challenges for widespread development of biofuels in a sustainable fashion.

Chemists Need Broad Perspective

Chemists and chemical engineers are not only employed in the lab, pilot plant or production facility. Many corporate executives have a degree in the chemical sciences. And, as is well known, the success and impact of a project relies on non-technical factors at least as much as the feasibility of a technology. Thus it is very important that chemists and engineers have a broad perspective of the life cycle impacts of alternative energy sources such as biofuels, both domestically and internationally. It is important for managers to have this perspective as they analyze potential projects so they can better understand the effects on their bottom line as well as consequences on society and the environment. Policy makers need to understand how policies to promote biofuels will impact more than biofuel production. Wise policies would promote efficient production and use of biofuels while minimizing the negative impacts, particularly the indirect impacts that are not always obvious. And chemists and engineers in the plant or lab should understand the potential positive (or negative) impacts their work may have so they can choose a field that matches their societal conscience while providing ample technical challenge.

Too often chemists only study the technical aspects of an issue without considering the broader impact of their work in society and on the environment. The purpose of this book is to bring together the views of experts in a variety of fields to broaden our understanding of the effects and potential for biofuels to help insure biofuel production is done the right way from both the scientific and policy views. To do this, we must have a more comprehensive perspective of the issues involved and ask questions that aren't obvious initially. "If corn is planted in place of soybeans for production of bioethanol in the U.S., how does that affect land use in other countries?" "What is the most appropriate policy for taxation of bioethanol produced outside the U.S. and its impact on the U.S. bioethanol industry?" "If the U.S. moves to use lignocellulosic materials for production of ethanol, how does that impact forests and rural communities?" "What is the real impact of biofuel production on emission of greenhouse gases?" Addressing questions such as these can influence the policy decisions as well as technical decisions such as feedstock source and the optimal size of the production facilities.

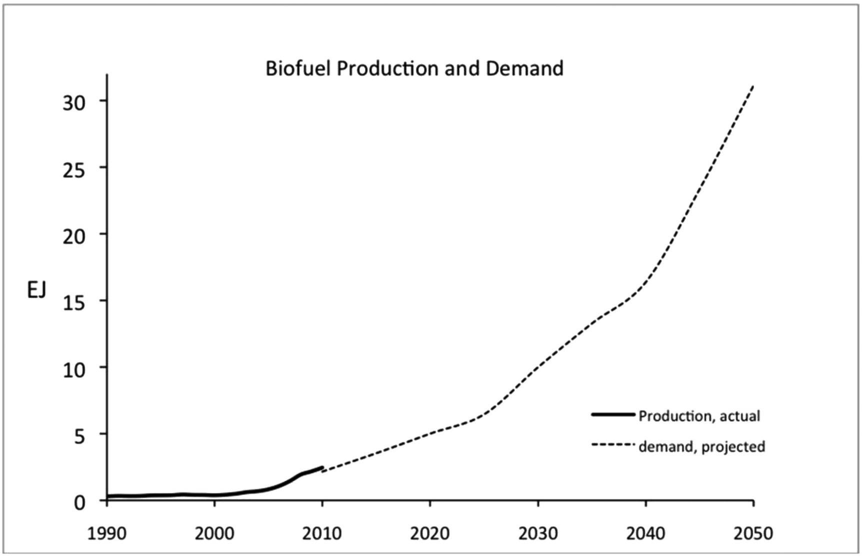

Figure 1. Past and projected global biofuel demand through 2050, data sources: past production BP Stat Review (1), projected demand IEA 2011 (10).

Similar to professionals in other fields, chemists and engineers have a desire to improve the world. We don’t want the products we create to cause adverse consequences for others. In the field of biofuels, much has been made of the food versus. fuel debate (or, more accurately, "feed versus fuel"). On the surface it seems logical that if crops are used to make biofuel instead of foodstuffs, there would be less food available and prices would increase. However, the balance is far more complex. While the amount of corn used for ethanol has increased in the US, the total amount of corn produced has also increased (9.4 billion bushels in 2000 to 13.1 billion bushels in 2010), with exports continuing to fluctuate in the range of 1.6 to 2.4 billion bushels between 1995 and 2010 (only 2007 was outside the range, at 2.6 billion bushels) (*11*). A counter argument can also be made that there is excess food production capacity in the U.S. and creating fuel from crops can help domestic farmers and lessens the price increase of petroleum-based fuel by decreasing petroleum demand. Keeping the price of petroleum based fuel lower can result in decreased overall expenses for consumers and actually may cause a favorable impact on food prices because the cost of fuel used in farm equipment impacts the price of the food. To further complicate such debates, the impacts vary in different regions of the world. Thus to make the best, most informed decisions, chemists in their roles as chemists, managers and policy makers need to better understand the non-technical aspects of their projects and their feedbacks, as well as technical challenges.

Issues and Biofuels

Biofuels are attractive because they offer the promise of a renewable liquid fuel source that can be produced in an environmentally responsible fashion while decreasing the production of greenhouse gases. In addition, they can be produced domestically which can have economic and security benefits. For these reasons, biofuel production has been subsidized in the U.S. and elsewhere. However, the production of biofuels remains controversial, in part due to the subsidies and concerns about the environmental impact.

Economic issues and current policy factors pose challenges to the potential for lignocellulosic ethanol in the short term. The U.S. is very close to producing enough ethanol to provide all gasoline at a 10% ethanol so to increase demand would mean increasing the amount of ethanol in the blend or significantly increase the use of flex-fuel vehicles and infrastructure to service them (*12*). This is further complicated by idle starch to ethanol plants which could be started up when economics improve and, despite the problems with using starch feedstocks, conversion of starch to ethanol is still cheaper than conversion of lignocellulose to ethanol (*12*). Despite the problems, there is value in pursuing the conversion of lignocellulosic biomass and other advanced feedstocks to ethanol and other fuels to help meet the need for liquid fuels and to help achieve a significant decrease in greenhouse gas emissions.

It is generally accepted that in the U.S. we need to move away from food/feed crops to lignocellulosic feedstocks to create truly sustainable biofuel production. Significant technical issues related to recalcitrance of lignocellulosic biomass and other feedstocks and the production of advanced fuels remain before they become viable on a large scale, but there is confidence the technical issues will be solved. Even after these technical issues are solved, many other questions will remain. It is not clear what the optimum lignocellulosic feedstock is and, much like the ideal energy mix, optimal feedstocks are likely to vary regionally. Feedstocks may include forest waste and cultivated plants, with the choice of the appropriate plants dependent on a number of factors. Harvestable biomass, water use, effect on soil quality and ability to grow these crops without competing with food crops for land are among the key issues (*13*). Ethanol, currently the most widely produced biofuel, is not as energy dense as conventional gasoline, and this has implications for land and other resource use requirements (*14*, *15*). Using rail and truck to move ethanol beyond the local or regional scale adds to cost (*16*). The lower energy density of biomass creates issues for transport of biomass to processing facilities. This is an issue related to the amount of energy required for transport compared to the energy output, and also the infrastructure necessary to move and store biomass, especially since most of the production is expected to occur in less developed rural areas (*16*). In addition, current petroleum infrastructure is not compatible with the corrosivity of ethanol, so that additional infrastructure needs to be built if ethanol were to be transported by pipeline.

Much can be gained by examining the biofuel production techniques of other nations. Brazil, for example, produced about 28 billion liters of bioethanol in 2009 (*17*), and annually meets about a quarter of its total road transportation energy demand (*18*, *19*), driven by a national ethanol program (*Pró-Álcool*) launched in the 1970s for security of supply. Although Brazil is using sugarcane as the feedstock for bioethanol production rather than lignocellulosic materials, there are common problems in biofuel production (*20*) they have addressed. For example, harvesting the crop in a sustainable fashion to preserve the quality of the soil is an issue for all crops and regions. Valuable lessons may be learned related to transportation, processing plant size and efficiencies gained by cogeneration of biomass not used for fuel. We need to be aware of the issues of creating biofuels as well as the approaches others have used.

Global biofuel production will continue to increase despite the significant technical hurdles which we need to overcome for large-scale production and distribution of biofuels in an economical fashion. Use of lignocellulosic feedstocks and production of advanced fuels and direct gasoline substitutes are still nascent fields. Along with the technical challenges, we need to be aware of the additional factors driving the demand for biofuels as well as understanding the multifaceted impacts of biofuels on the environment and the inhabitants of the planet. Understanding these issues will aid in the successful development of biofuels that contribute to the energy mix with minimal adverse impacts.

This book originated with a symposium held at the 2010 National Meeting of the American Chemical Society devoted to discussing potential benefits and pitfalls of biofuels in a range of disciplines to provide additional context to the ongoing technical development. In the remainder of this book, speakers from the symposium and other invited authors present their perspectives on the biofuels from a variety of professional perspectives.

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Chapter 2

Projecting an Energy Future: Biofuels, Bioenergy, and the Importance of Regionality in Scenarios and Potentials

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The development and expansion of sustainable biomass-based transportation fuels is part of a much larger energy context. While there is a tendency to look for a "silver bullet" solution to the interrelated climate and energy dilemma, the problem's very nature means that the solution is multidimensional, requiring flexibility and forethought to deal with inherent uncertainties. Regional and local drivers for development in emerging, pre-emergent, and less developed countries add more complexity by creating multiple priorities for resource allocation. To provide an accessible vision of the future and choose a sustainable path that includes biofuels, it is necessary to compare forward-looking scenarios that encompass both global sources and global impacts. These scenarios must accurately reflect the regionally accessible potential resources as well as the sectoral balance and cross-sectoral competition for those resources, but control the level of detail. This paper introduces biofuel feedstocks and technologies and discusses how biofuels can provide an engine for sustainable development while also considering the influence of regional factors on scenarios and potential estimates.

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
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Introduction

The intersections between energy and climate and energy and development that underpin modern society put a unique strain on our global resources. As the world's population continues to grow, so too will demand for energy, food, water, and other resources. This demand will increase the strain put on environmental systems. As climate change results in increased fluctuations in temperatures and precipitation, the strain will become more acute. Population growth is projected to be driven mostly by growth in the developing nations (Figure 1) and accompanied by a shift from rural to urban densities (*1*). As the emerging economies become more affluent, and pre-emergent economies advance, consumption will increase as personal mobility and meat consumption increase. These are energy-intensive changes.

In 2008, global energy consumption was just under 400 EJ (Figure 1); in 2035 it is projected to reach above 550 EJ (*2*). The bulk of global energy is supplied from fossil fuels, almost 90% in 2008 (about a third from petroleum), with essentially the same mix predicted for 2035 (*2*). About two-thirds of the energy consumed worldwide is used industrially, and about a quarter serves transportation. Currently, renewable energies are only about 3% of supply, and estimating how much it might expand is challenging because technologies are young (*3*) and likely to be disruptive, changing suddenly and quickly (*4*).

Recovery of fossil sources will not get easier, and is likely to become more expensive and to increase environmental burdens. The combustion of fossil fuels transports previously sequestered carbon into the atmosphere and thereby increases atmospheric CO_2. All energy accounts for two-thirds of global greenhouse gas emissions annually, and the transportation sector about 15% of the total (*5*). Total energy is responsible for an even larger fraction of emissions in the US, 87%, and the transportation sector along accounts for 31% of US greenhouse gas emissions (*6*). Meeting CO_2 abatement goals will require both efficiency gains and replacement of fossil fuels (*7*). Additionally, fossil resources are not uniformly distributed (*8*), and insecurity of supply has provided a strong impetus for alternative energies (see, *e.g.*, the US Energy Independence and Security Act of 2007 (*9*)). As it stands, the current global energy system is not sustainable over the long term.

Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," as defined by the WCED in 1987 (*10*). Sustainability has three legs: social, environmental, and economic. Depending on defined priorities, each of the three components of sustainability may or may not be considered equally important, a reflection of local or regional constraints and drivers. However, true long-term sustainability requires that all three conditions be met.

There is no single, 'silver bullet' solution to our global energy-climate dilemma. Because our energy system encompasses many sectors and must supply a range of energy carriers and services, in order to ensure long-term sustainability, many different technologies will contribute to the portfolio. Biofuels fill a particular need; they can substitute directly for liquid fuels that can be used for heavy and light duty transport. They can also support some lower-complexity and low-infrastructure power generation options when supporting infrastructure is absent. Because they are derived from biomass, which can be produced almost anywhere, unlike fossil resources that are very non-uniform, and because there are conversion technologies for almost any level of local infrastructure, biofuels will be a crucial energy supplier in many areas. It is important to understand how they will be able to contribute to a sustainable future.

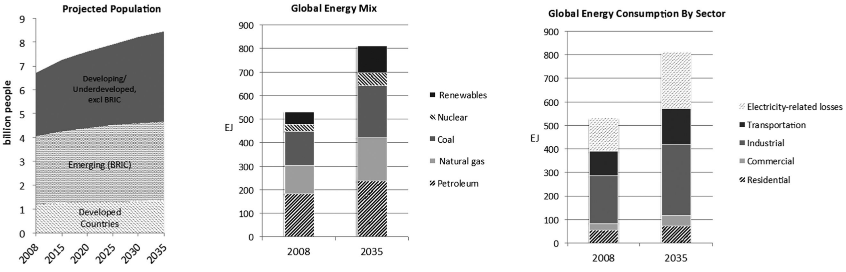


Figure 1. Current and projected population, energy mix, and sectoral energy demand globally for 2008 and 2035 show large increases. Data from references (1) and (2).

Local factors, from weather to agricultural practice to culture, affect biomass and bioenergy strongly, resulting in more variability both temporally and spatially. Including bioenergy and biofuels in deployment scenarios requires a multi-scale approach. Rather than a technical overview of scenarios and bioenergy/biofuel potentials, this paper seeks to provide an introduction to some of the key concepts that may be relevant to scientists active in this emerging area to better understand regional context and assist in future projection. First, it provides a brief introduction to biofuel feedstocks and technologies, followed by estimates of potential availability. Deployment scenarios are discussed in the following section, starting from developmental priorities, and the chapter concludes with some of the social and other broad sustainability issues related to biofuels.

A Brief Overview of Biofuels

Bioenergy is an energy carrier derived from biological sources, usually biomass; it includes electricity from biomass, primary use, biogas, and biofuels. Biofuels generally refer to liquid energy carriers derived from biomass, such as ethanol or BtL (biomass-to-liquids) diesel, which are used for transportation. Common biofuel feedstocks are listed in Table I.

The energy in biomass was harvested from the sun and the carbon from the air. Plants capture solar energy using carbon captured from the atmosphere. Only a small fraction of the incident radiation can be captured and converted into chemical bonds. About two-thirds of the incident radiation is either outside the usable spectrum or reflected and so does not enter photosynthesis. Losses during carbohydrate synthesis and smaller losses occur at other points. Photosynthetic efficiencies at the end of the cascade are 4- 6% in grasses (*11*) (algae is slightly higher). While it is a low-efficiency system in comparison to photovoltaic systems, the abundance of available light, the presence of plants in the natural landscape, and the fact that plants contain their own conversion mechanisms, make biomass a very effective capture and storage system for energy. This biomass can be used as a feedstock for the conversion technology, analogously to petroleum, to capture the energy stored in the plant and turn it into an energy carrier serving a particular purpose.

Table I. Some Common Biofuel Feedstocks

Starches/Sugars	*Oil Seeds*
Corn (Maize)	Soybean
Wheat	Palm Oil
Cassava	Rapeseed
Sugarcane	
Sugar beets	Jatropha
Sweet Sorghum	Camelina
Agaves (beverage)	
Herbaceous Energy Crops	*Woody Energy Crops*
Residues	*Residues*
Corn stover	Forest thinnings
Wheat Straw	Sawdust
Sugarcane bagasse	Construction residues
Oil palm husks/bunches	Woody yard waste
Fruit juice and pulp	
Non-woody yard waste	
Perennial	*Perennial*
Miscanthus x giganteus	Poplar
Switchgrass	Willow
Napier Grass (*Pennesetum purpureum*)	Pine
Energy cane	Eucalyptus
Sorghum (biomass)	
Agave (fibrous)	

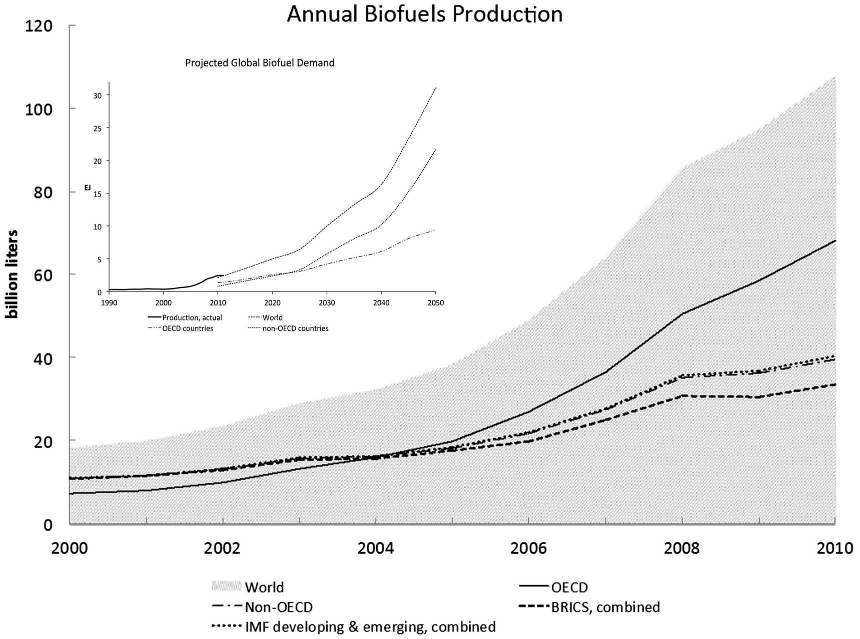


Figure 2. Global biofuels volumes produced and projected. Data from references (8) and (13).

Feedstocks fall into categories based on extent of current usage and position in the research, development & deployment (RD&D) trajectory. First generation crops use fairly mature technologies and are widely deployed. They include grains such as corn, wheat, or sorghum, as well as sugar beet and sugar cane; oil seeds are also first generation. Current biofuel production is mostly bioethanol in North and South America and biodiesel Europe. The last decade has seen large increases in production of first generation biofuels (see Figure 2). Production in 2010 was 105 billion liters (*8*). Developed countries started expanding strongly in 2004, while growth in developing countries has been slower. Brazil and the US are the largest contributors in each group (*12*). Production is expected to increase at a fairly rapid pace (*13*) (Figure 2, inset), driven by strong demand in the developing world.

Advanced feedstocks depend on more complex and early-stage technologies still being developed; they include lignocellulosic biomass, including grasses, woody biomass, *etc.*, and algae. The product may be ethanol, longer alcohols, or hydrocarbons that may go to direct substitutes for liquid fuels. The advanced category is sometimes also split into second generation (nearer-term, such as lignocellulosic crops) and third generation (further term; includes algae). The categorization is also sometimes based on estimates of impact on food supply chains, where first generation feedstocks are frequently also used as livestock feeds while advanced feedstocks are those not expected to directly affect food

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

supply chains because they are not edible. Advanced feedstocks and technologies generally use non-edible plants or non-edible portions of plants. The discussion here focuses on biomass from traditional-style agriculture, as it can readily integrate with existing agricultural operations. Algal biofuels have a longer time horizon. Algae are commercially used now to produce high value products; the technology remains too expensive for commodity products. There has been a lot of investment and research in the last 40 years into algal species. Details of this emerging technology and the challenges and steps being taken to overcome them are discussed in Milne, et al (*14*).

Agricultural residues, such as stover or straw, and perennial crops, either herbaceous or woody (see Table I) are targeted for advanced biofuels. Perennials are lower impact than annual row crops, since they have much reduced tillage and lower erosion, and generally much lower chemical inputs. Some of the potential feedstocks for lignocellulosic biofuels, such as *Eucalyptus* spp. (*15*) or prairie cordgrass (*Spartina* spp.) (*16*), are salt tolerant or are tolerant to other stresses and conditions that make using some of the land that that has become damaged or degraded more viable. Perennial energy crops show smaller yield decreases on degraded or marginal lands in the face of other stressors (*17*). Feedstocks with such characteristics are potentially valuable opportunities in developing and underdeveloped countries, where land is frequently more challenged, either because of strain, degradation, or resource and/or infrastructure limitation. In addition to *Agave* or *Eucalyptus* (*18*), crops such as *Jatropha curcas*, *Opuntia ficus, Arundo donax, Pennisetum purpureum, Pongamia pinnata*, sugarcane, sorghum, *etc*. (*19–22*), are possibilities to fill such niches, particularly in developing and less developed countries.

A large portion of annual bioenergy is from traditional biomass combustion, with losses of 80-90% (10-20% average efficiency) (*12*). Modern bioenergy supplies just under a quarter of the primary energy as traditional biomass does, but delivers about the same secondary (useable) energy as traditional burning does because the efficiencies in modern conversion technologies are so much higher (even up to 90% in some modern furnaces) (*12*). To supply energy services other than heat and power, however, the energy in biomass needs to be transformed into a different energy carrier, such as liquid biofuels for transportation.

Plant cell walls are constructed of lignocellulose, a complex matrix of polysaccharides and lignin, an irregular polymer protective coating. Cellulose fibrils make up the wall's core. Cellulose is a polymer of glucose, a readily fermentable 6-Carbon sugar. The fibrils are coated with hemicellulose, made up of 5- and 6-Carbon sugars, predominantly xylose that can also be fermented by some microbes. This structural matrix provides stability and protection for the plant, making the extraction of these sugars challenging. The plant cell wall evolved to be extremely resistant to degradation; it is stable and recalcitrant.

Routes for creating biofuels from the cell wall follow two paths. The biochemical or microbial platform is based on partial breakdown of the wall chemically or biochemically to release the cell wall sugars for microbial fermentation or chemical conversion. The residual lignaceous solids are commonly combusted for process heat and power. The thermochemical platform deconstructs the wall partially (torrefaction or pyrolysis) or completely (gasification) to syngas (CO and H_2) followed by catalysis to fuel molecules. Most lignocellulosic biofuel technologies produce ethanol, while thermochemical routes produce mixed alcohols or direct hydrocarbon equivalents of gasoline or diesel. Technologies are also continuing to develop around microbial production of hydrocarbons. Some of the more common biofuel carriers conversion technologies are shown in Table II, along with yield ranges and some characteristics important to matching technology with local or regional needs for different levels of development. Biogas is shown for comparison; it is extremely scalable and widely used for to provide cleaner fuels for rural household use (*23*) all the way to large-scale industrial use (*24*).

Conversion of biomass to fuels in a biorefinery is analogous to petroleum refining. As in the refining of petroleum, conversion of biomass generally results in several co-products. Nearly every biorefinery produces heat and power for use in the conversion process, and sometimes export to the grid. Brazilian cane ethanol plants are mostly self-sufficient (*25*) and export large amounts of electricity, supplying about 2% of Brazil's total electricity in the 2010/2011 season (*26*). Other co-products include livestock feed supplements, especially for high-protein content grains or oil seeds (*27*) and some lignocellulosics (*28*), and a range of bio-based chemicals and biomaterials, such as resins, adhesives, composite materials, and precursor chemicals (*29*). The ability to produce additional value-added products reduces final costs for the fuel product and can help distribute the environmental burden.

Much of the current interest in lignocellulosic fuels originates with governmental mandates, and the recognition that such fuels are derived from a non-competitive feedstock. They are perceived as being implementable in a manner that minimizes adverse resources competition. Currently, the US's primary biofuel is corn ethanol. The Renewable Fuel Standard, the US federal mandate, is for 36 billion gallons of biofuel, but caps corn ethanol at 15 billion gallons per year. Since population and demand projections suggest that we will continue into an era of more constrained resources, future sustainable technology is likely to place even more emphasis on maximizing efficiency. In essence, this reduces to maximizing capture of both the carbon and energy in the starting material. Some bioenergy technologies are mature and well established, others are young and potentially disruptive (and others are almost entirely speculative), but even the well-established technologies have room for improvement (*34*). There are a number of overviews of feedstock research targets and detailed technology improvement scenarios and estimates for a range of technologies (*12*, *35*).

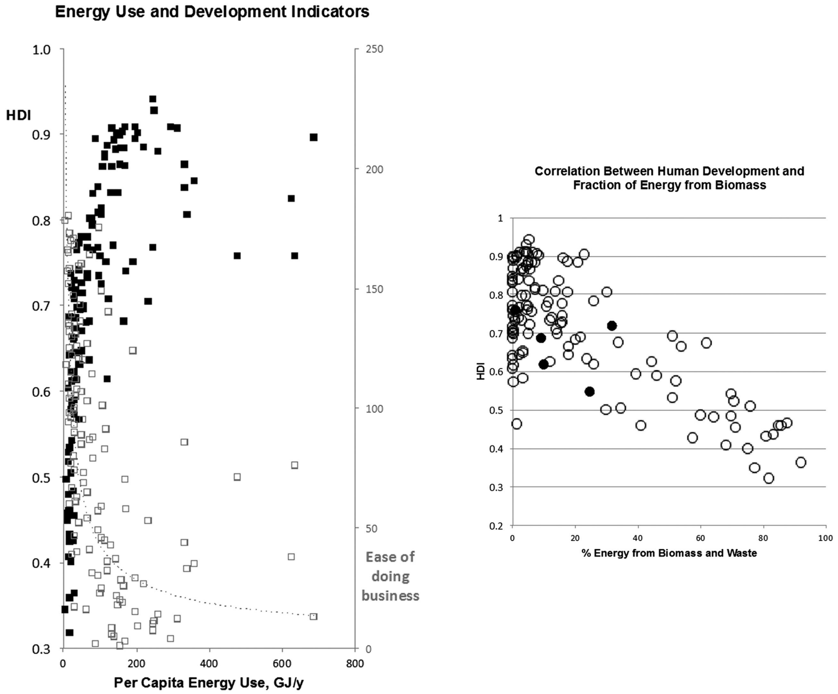
Advanced conversion technologies are still nascent or emerging, so are vulnerable to the risk and uncertainty associated with large capital investment and the development trajectory of conversion processing plants (biorefineries) for scale-up from demo to pilot to finally commercial scale. Scale-up is both challenging and expensive. Additional challenges are associated with policy uncertainty and whether there will continue to be sufficient support to nurture new technologies in such a way that this new technology can grow while it isn't competitive with well-established (but less sustainable) technologies, the model used to facilitate the development of Brazil's cane ethanol industry (*25*). Evaluating the value of such support (both for investment and research) and its potential to meet global and local sustainability goals depends on projecting forward the amount of resource and recoverable energy and assessing possible impacts.

Table II. Characteristics of Some Selected Biofuel Technologies

Product	*Technology*	*Technical Complexity*	*Maturity of technology*	*Infrastructure needs*	*Scale*
Ethanol	Biochemical/Fermentation	+	++	+	●● to ●●●●
		Feedstock	Productivity MT/ha/yr	Fuel Yield L/ha	
		Corn - Grain [a]	7 - 10	2,900 - 4,200	
		Sugar cane [a]	80 wet (11 MT sugar)	6,900	
		Sugar beet [e]	46	5,000	
		Agave spp.[a]	10 - 34	3,000 - 10,500	
		Cassava [e]	10 - 14	1,500 - 2,100	
		Sorghum	1 - 5[c]	500[e]	
Biodiesel	Chemical/ Transesterification	+	++	+	● to ●●
		Feedstock	Productivity MT/ha/yr	Fuel Yield L/ha	
		Soy bean	1 - 3[c]	500-600 [e]	
		Rapeseed	3 - 4 [f]	1,200 [e]	
		Oil Palm [e]	18 - 21	4,100 - 4,700	
Ethanol	Biochemical/Fermentation - Lignocellulosic Biomass	++	–	++	●● to ●●●
		Feedstock	Productivity dry MT/ha/yr	Fuel Yield L/ha	
		Corn - Stover [a]	3 - 6	900 - 1,800	
		Switchgrass [b]	4 - 20	1,150 - 7,450	
		Miscanthus[a]	15 - 40	4,600 - 12,400	
		Sugarcane Bagasse [a]	10	3000	
		Poplar (coppice) [a]	5 - 11	1,500 - 3,400	
		Eucalyptus spp. [d]	9 - 31	2,700 - 9,300	
Renewable Diesel	Thermochemical/Fischer Tropsch	++	– –	+++	●●●●
		Feedstock	Productivity dry MT/ha/yr	Fuel Yield L/ha	
		Willow (coppice) [b]	5 - 11	1,200 - 3,700	
Biogas	Anaerobic Digestion	–	+++	–	○ to ●●●
Notes	[a] Reference *(18)*. [b] Reference *(30)*. [c] Reference *(31)*. [d] Reference *(15)*. [e] Reference *(32)*. [f] Reference *(33)*.				

Development and Bioenergy

Energy use underpins social development. It correlates to most development indicators and goals. Quality of life is frequently represented with the human development index, HDI, an aggregate metric that combines health, education, and income/standard of life metrics. Figure 3 shows the HDI relationship to *per capita* energy use (*36*, *37*); at the lowest levels of development there is very little energy use per capita relatively speaking. As the level of development increases, the energy use increases. This illustrates a chicken-and-egg situation: more energy supports additional growth, growth makes more energy resources available through markets and/or recovery or extraction. The ease of doing business shows the opposite trend (Figure 3, panel 1, right axis): the more developed the economy/country is, the more energy is used/available, and the easier it is to do business in a country. The number of researchers in R&D per million people in a particular country correlates in the same manner (*37*). In combination, these suggest the ability of an area to support detailed business and growth; that is, the presence of an existing underlying infrastructure to support development. They contribute to what sort of development will have the highest impact, and how attractive a region will be for investment supporting development.



Energy Use and Development Indicators

Correlation Between Human Development and Fraction of Energy from Biomass

Figure 3. Energy-correlated responses in national developmental indicators. Data from references (36) and (37).

The intersection between bioenergy and development benefits not just the most developed countries, but potentially can provide benefit across development levels. The level of development correlates strongly with composition of the energy mix as well as to per capita energy use (Figure 3). Countries lower down on the development scale generally have a large fraction of biomass-based energy in their energy mixes. The top boundary of the United Nation's Development Program's (UNDP) lowest level of development corresponds to about two-thirds of energy from biomass. Developed countries generally have much lower fractions of biomass in their energy sources, most under 20%. The fast growing emerging economies, the BRICS (Brazil, Russia, India, China, and South Africa), are scattered throughout the one-third or lower biomass energy range (filled dots). A transitional stage is fairly clearly suggested in the mid-range of the development index. It is abundantly clear that biomass will be a valuable resource in shifting energy availability. Biomass has forever been one of the primary sources of energy, and it is distributed in useful ways that provide more egalitarian access; current high-percentage biomass mixes are correlate to development indicators of about 0.5 or less. Changing what sorts of technologies are used to harness biomass energy can contribute to raising that.

Investment in agricultural growth is a major engine for improving development level. At low incomes, an investment in agricultural growth produces a large increase in income (about 6%, 4%, and 3% for the bottom three income deciles) (*38*), resulting in substantially more benefit to the poor than does growth in non-agricultural sectors, which actually correlates to a decrease in income for the poorest groups. Only for the most affluent, those in the top 10% of incomes, does non-agricultural growth provide more increase in income than does growth in agriculture. Thus, for the most vulnerable populations, increasing agricultural development has a dramatic impact on income, and so on quality of life and other developmental indicators that correlate to income. Overlaying this benefit from growth in agriculture with the fraction of energy coming from biomass suggests a valuable opportunity to support development both in terms of energy and income.

This becomes a bigger issue, then, when we incorporate the quality of land that is available and what stressors are locally dominant and how they will affect the land going forward. If agriculture is going to be a, or the, primary driver for development for the most vulnerable populations, then the issue of how land, and other resources, are managed becomes extremely important if the development is to satisfy sustainability tenets and benefit the most vulnerable.

Estimating the Potential

Bioenergy and biofuels, as primary renewable energy options, are expected to contribute increasing amounts of energy to meet growing demand. To what extent biomass-based energy can be included depends, of course, on how much is available, which is a function of land availability and quality, crop selection, agronomic practices, time horizon, competing uses, energy carrier and conversion technologies, and intersections with the local landscape and international trade.

Fitting bioenergy into scenarios describing future energy mixes to assess their net effects on environmental, social, and economic sustainability in comparison to alternative uses and energy mixes depends on quantitative or semi-quantitative estimates of contributing resources under particular assumptions.

Biomass assessments come in two types: estimates of the amount needed to meet a particular goal (demand-driven), or the potential available based on resource availability and constrained by competition. Though potential is used for both, here it is used to indicate an endogenous quantity rather than meeting an externally set goal, because the question of interest is what might be possible. This can later be assembled into scenarios to support decisions about use and allocation.

There are three levels of biomass or bioenergy potentials (*39*): theoretical, geographic and technical (also sometimes called recoverable) potentials. Those potentials are generally independent of value judgments. They are further constrained to economic (sometimes called market), sustainable (generally meaning environmentally sustainable) here labeled "ecological" potentials, and finally the implementation potential itself. The sustainable potential is the overlap among the economically limited potential, the socially limited potential, and the ecologically limited potential. Realistically, the implementation potential will be some function of the combination of the set but unlikely to be the perfectly intersecting sustainable potential. This framework can be extended to most resources. The relationship among these potential types is illustrated in Figure 4.

The potential types are hierarchical, from estimates of possible available land, to estimates of potential biomass production on that land, to estimates of recoverable energy via a particular technology. The theoretical potential for a particular parcel of land is its net primary productivity (NPP), a modeled estimate of what the land could yield (the above-ground biomass). That value can be affected by many factors, among them how much land and of what type and quality and the balance between temperature, water and light. Perfect growing conditions are not easily found, so it is optimized by matching crop and management practices to the limitations. A wide range of bioenergy feedstocks makes it possible to find a viable option almost anywhere, subject to some compromises in yield. Selecting a particular bioenergy crop or set of crops determines the geographic potential.

Practical considerations constrain the theoretical and geographic potential: whether it is physically accessible or mechanically accessible (*i.e.*, can it be harvested); what the specified or prioritized goals for sustainability are for a given parcel of harvestable biomass and what energy carriers and conversion technologies are the basis for the study. This gives rise to the technical potential. Geographic and technical potentials are both dependent on time horizon chosen, because they may include such factors as improvements in crop yields or practice or innovation in harvesting technologies.

The intersection of the technical potential with what is economically viable is the implementation potential. The implementation potential is also influenced by sustainability priorities, that is by the economic, social, and ecological limits in a particular landscape. The most important parameters are set in each particular context, and will lead to balancing decisions. Context will dictate if it is possible or reasonable to achieve the sustainable potential, which is the lowest potential of the set (generally only identified as possible from very privileged perspectives). Alternatively, other needs may support harvesting more than environmentally sustainable because doing so could provide benefit elsewhere, for example, increasing social sustainability by increasing employment or greater access to energy. Specific regional priorities dictate implementation potentials and may not be transparent.

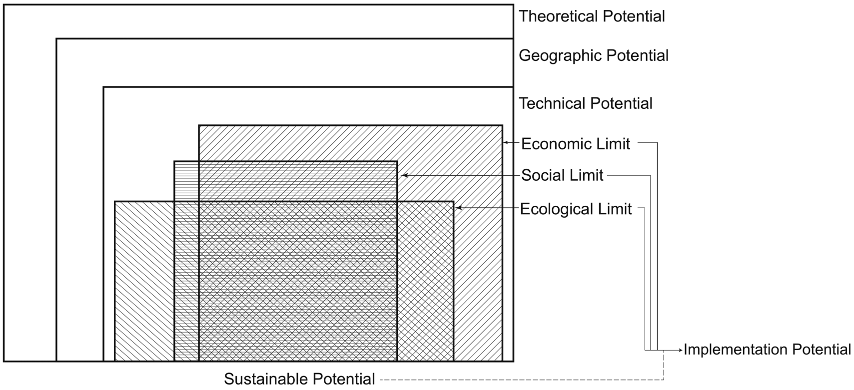


Figure 4. Boundaries used to determine various levels of potential biomass/bioenergy availability.

Biomass potentials show enormous variability across analyses, from 200 - 1600 EJ in 2050 in one meta-analysis (*40*). The range is so large for several reasons. Some are underlying differences in the study, such as differences in crops or land types chosen, decisions about limitations on lands used, or management practices. Others differences are in assumptions for yield and productivity, allocation of competing resources like water, or weather and climate factors. Depending on the goal of the assessment, time horizons may not match up and the potentials will respond to differences in estimates for innovation or technological maturity and advances in harvest and recovery. In addition, when the potential is based on energy output, conversion efficiency and transfer losses, along with end use efficiency and delivered service (aka "functional unit") all contribute to the calculated value and can vary widely from scenario to scenario. Environmental constraints can be applied at several points in the hierarchy, and can also affect the value. Differences in estimates of land availability and/or quality of land available and assumptions of biomass type and yield are accountable for most of the variation in reported biomass potentials (*41*).

Table III shows some results of applying sustainability criteria to potential assessments. Decisions about sustainability priorities dictate inclusion or exclusion of various land and/or crop types. Their application decreases the estimated available biomass energy. The technical plant-based (excluding waste) bioenergy potential for is shown in the table as well; the combined bioenergy potential in 2050 is 115 - 1030 EJ/y, depending on surplus land estimates and logistical factors (*42*). While informative, such broad potentials (or, indeed, any large-scale aggregated estimate of potential) provide qualitative or relative insight. They are generalizations; from the point of view of determining the best bioenergy option locally, and its potential and impacts, such generalizations are less useful. They do not provide direct insight about what energy carrier or service is preferred and which technology should be used to convert the biomass given local physical, social, or political conditions that are difficult to include without stakeholder participation. Technical and economic potentials are most common, in part because applying the social and environmental limits to determine sustainable potential is an inherently localized activity. Regional factors make the "best fit" highly specialized because they are predicated on the local constraints, drivers, and goals for use of the resource.

Regional Specificity in Scenarios

Scenarios are used to guide planning in "circumstances of decision-making in which information bearing on relevant facts, (or states, events, or propositions) is scanty, marked by gaps, obscure and vague, or on the contrary plentiful, precise, but highly contradictory," because it can facilitate identification of "the reasonable choice among given alternative actions on the basis of highly incomplete information" (*47*). Long term policy planning is devoted to making decisions under such conditions, so scenario analysis is a necessary tool.

Table III. Examples of Different Bioenergy Potentials Based on Application of Various Sustainability Criteria

Sustainability criteria applied	*Resulting land type*	*Feedstock(s) notes*	*Energy EJ/y*	*Source*
"Food first" (with integrated food, livestock, bioenergy)	all agricultural, normal diet	crop surplus, residues	64	(*43*)
	all agricultural, frugal diet	crop surplus, residues	161	
Biodiversity and environmental protection	salt lands only	woody biomass	42	(*44*)
	+ minimal agricultural land	woody biomass	56	
Mixed: Food security, minimal competing use, avoid protected lands and forest	degraded lands	grassy energy crop	151	(*17*)
		woody energy crop	193	
Mixed: Avoidance of competition for food, preservation of soil carbon	abandoned agricultural land	woody	32 - 41	(*45*)

Continued on next page.

Table III. (Continued). Examples of Different Bioenergy Potentials Based on Application of Various Sustainability Criteria

Sustainability criteria applied	*Resulting land type*	*Feedstock(s) notes*	*Energy EJ/y*	*Source*
Food Security: No competition for food or feed, minimize undernourishment	surplus agricultural land	low technical advances	212	(*46*)
		high technical advances	1272	
	agricultural and forest residues only	residue-specific	76 - 96	

Range of primary estimates for biomass (not wastes) (42)

Land Type	*Land Area*	*EJ/y in 2050*	
Surplus on Current Agricultural Land	1-3 Gha (0-4)	100 - 300 (0-700)	woody energy crop
Marginal Land	1.7 Gha	0 - 110	woody energy crop
Agricultural Residues	under production	15 - 70	
Forest Residues	under production	30 - 150	high logistic limits to technical potential

Two major benefits of the approach are that it enables analysis of impact and risk, and that it allows planners to deal with high degrees of uncertainty. Uncertainty underpins risk management. The scenario framework helps us to identify it, understand where it comes from, and then account for ways in which such uncertainties could alter outcomes. Analyses are then possible to evaluate to what extent those altered outcomes increase or decrease risks and risk-event probabilities. These are valuable for any nascent or emerging technology that couples to multiple sectors and involves human behavioral and market responses. Both of these are even more crucial for long-term sustainable energy system development, and to bioenergy development in particular, because of the scope of the problem.

Because there are so many confounding factors affecting future possible biomass and bioenergy yields, and so many possibly decision routes, many sets of options need to be compared. Using explicit, regionally specific priorities to filter among the possible outcomes or solutions suggested by the scenario exercise allows identification of alternative pathways in the event that priorities change, and enables more stakeholder participation through scenario building exercises. It is also possible to create hybrid potentials that weight the importance of particular goals rather than picking a winner.

Biomass provides flexibility to accommodate local needs, because there are many routes through which it can be converted to an energy service. Although many different energy carriers are accessible, each has a different efficiency. The wide variety of feedstocks, products, and technological complexities correlates to local sustainability priorities.

Deployment scenarios for biofuel technologies are complex and very sensitive to regional or local resources and structures. Figures 5 and 6 map out some of the components that are addressed to incorporate biofuel deployment scenarios on their own or as part of a larger scenario exercise. These are just some of the influential factors for regional variation in biomass-based refinery deployment. They include issues that may vary regionally and influence choice of technology, energy carrier, or deployment model and affect scenario narratives and outcomes.

Factors in the location and organization tree (Figure 5) will influence decisions about whether and where to build (siting, yields, productivity, *etc.*) and the optimal supply chain organization. Factors in the biorefinery tree (Figure 6) will impact the structure and products chosen the biorefinery and its integration with local actors. Many of the factors appear in multiple categories, or tightly depend on selections made in other categories.

While the technologies, in principle, are independent of location, in practice the available resources, infrastructure, political and cultural drivers affect the extent to which a technology has been or can be adopted in a particular area. Thus biorefinement capacity potential and development vary by region, and may have substantial heterogeneity even below the regional scale. This is one of the difficulties making decisions based on aggregated bioenergy potentials.

For example, the presence of many competing uses for the best available land makes degraded or damaged lands valuable, if they can be used or improved. Phytoremediation needs can thus provide a driver for bioenergy crop choices, since the crop can be used for something other than human consumption. Eucalypts can accommodate a large range of contamination in soil and still provide reasonable (if small) yields, modeled average of about 3 dry tonnes yearly (*48*), as can grasses like the dense-stalked prairie cordgrass (*Spartina* spp) that exude salt on leaves, removing a fraction of the salts in harvested tissues (*16*). Choosing such a feedstock can decrease land salinity over a sufficient time horizon. This then influences the choice of biorefinery technology, because the technology needs to be able to handle lower biomass throughput and increased salt or metals in the feedstock.

The components relating to bioenergy deployment scenarios need to incorporate biofuels into long term decision support scenarios are both broadly general and location specific. They include constraints and drivers such as policy instruments, market forces, and existing or necessary supply chain structures. Evaluating sustainability impacts based on these involves accounting for local and distant effects, many of which are coupled to other influences.

Ideally all three of the sustainability tenets are taken as equally important, but one aspect usually emerges as dominant. In discourses in the industrialized nations this is usually environmental sustainability, which involves paying a premium for more environmentally conscious products. Energy security is frequently cited as a primary driver for alternative energy or increased production of conventional fuels; it fits most closely with economic sustainability for the industrialized nations. Social sustainability and economic sustainability pair readily, but cultural components may tie more closely with environmental (*e.g.* landscape structure and historical land tenure).

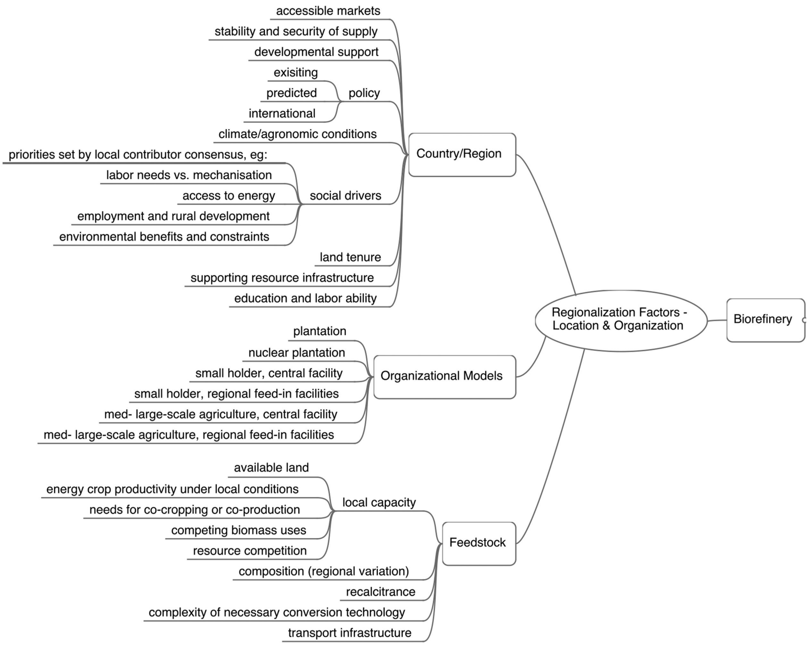


Figure 5. Some regional factors contributing to location and organization aspects of biofuel deployment scenarios.

More challengingly from a perspective of equitable global development, the same tenets function differently across different strata. Economic sustainability means something different at different developmental levels. At the upper levels (high HDI), it tends to mean wealth generation and corporate competitiveness. At the lower levels of development it tends to mean poverty mitigation. This is particularly important in setting goals for scenario comparisons in regional and developmental contexts. A higher weight may be placed on economic development or on socio-economic development and less on environmental for less affluent communities, while others may have the luxury of setting environmental protection as the primary goal even though it may result in lower productivity. In addition to income-related differences, regional heterogeneity in things like available transport infrastructure, or access to energy, or available physical resources like water or high quality soils create different regional or local constraints and drivers for using biomass, and multiple priority sets. For example, including selection criteria in the scenarios that emphasize variation when other criteria are balanced, increasing the landscape's structural diversity (*49*). The different ordering of priorities results in different filters for options in scenarios, as well as differences in the criteria used to judge possible outcomes.

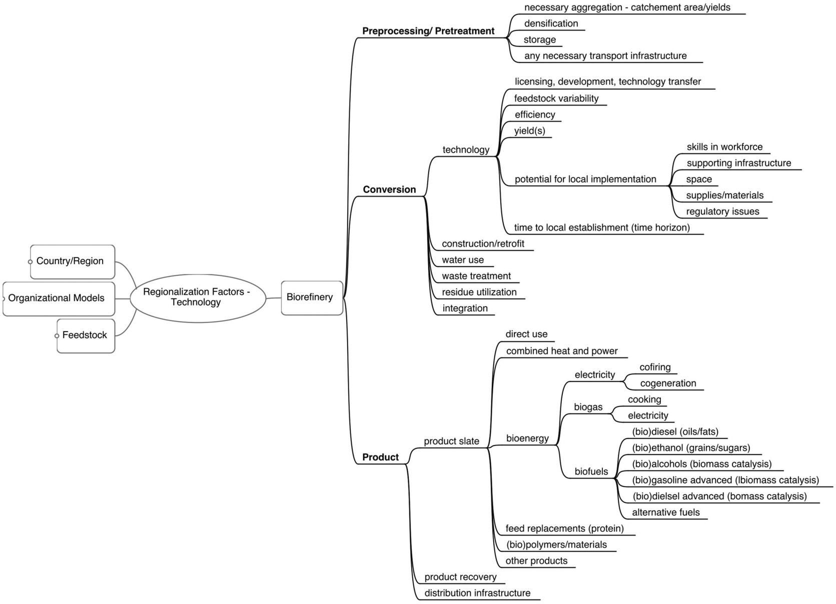


Figure 6. Some regional factors contributing to biorefining aspects of biofuel deployment scenarios.

Conclusion

Discussions around the annual climate summits bring to the fore mismatches between priorities for developed and developing nations each year. These disparities can, in part, be reconciled by emphasizing solutions that provide direct benefits to stakeholders in developing nations while addressing worldwide energy and climate mitigation needs. Regionalized or even localized feedstock, cropping, and conversion approaches have the potential to meet these criteria, if they capture the emerging technologies. Scenarios capturing this detail are needed to evaluate paths to a more equitable and sustainable future.

Energy needs are strongly location and goal dependent, and will continue to grow. The intertwined climate and energy crisis facing the planet will not be met by a single ‘silver-bullet’ solution but by many solutions, including biofuels and bioenergy where appropriate. Finding a good mix of those solutions requires accounting for many factors and dealing with large amounts of uncertainty. Limited resources will need to be used in optimal ways reflecting the global diversity of lands, cultures, and climes. We already think of bioenergy as part of the landscape. In fact, it is part of a sustainable, multifunctional landscape that provides services for a range of populations at different levels of operational complexity. To explore the real benefits and impacts of possible paths forward, and the role bioenergy may play, scenarios must reflect the regional mosaic of resources, social and cultural needs, and best-fit options.

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Chapter 3

The Effects of Stakeholder Values on Biofuel Feedstock Choices

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Biofuels, like any emerging technology, have the potential to cause ethical dilemmas by exposing the colliding values of multiple stakeholders. Policy is an instrument used to buffer these collisions. In the case of biofuels, policy must seek to balance the postulated positive and negative environmental and socioeconomic effects of biofuels expansion and the associated development of new feedstocks. At best, this is a precarious endeavor. The biofuels community faces extreme ethical scrutiny to account for not only the direct effects of widespread adoption but the indirect effects as well. For example, biofuels used in the U.S. and E.U. must account for not only their own carbon footprint, but any emissions associated with market-mediated land-use change in other countries. This type of accounting requires development of new analytical methodologies and improved data coverage. In large part, the interactions between stakeholders surrounding these controversies will determine what role biofuels play in a range of issues including: (1) our future energy portfolio; (2) the strategies adopted to mitigate climate change; (3) changes in agriculture including the types of feedstocks used and how these feedstocks are grown; and (4) how to best manage the increasing demands of humans on resources and the environment. The acceptance of biofuel feedstocks as "renewable" or "sustainable" epitomizes the myriad ethical issues accompanying biofuel expansion. In this chapter,

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

several biofuel feedstocks and the criteria by which different stakeholders judge them is examined to illustrate some of the alignments and conflicts in stakeholder values and how they affect feedstock choices, especially in the nascent cellulosic ethanol industry.

Introduction

Biofuels are, in simple terms, energy storage molecules derived from renewable biological materials (biomass), mainly carbohydrates and lipids. The primary motivation for developing fuel from biological sources is to move from non-renewable fossil energy to energy sources that can be produced sustainably. Biofuels are an important part of this effort (*1–4*). Although there are several routes to producing renewable, low-carbon electricity (e.g. wind, solar, geothermal) and some of these could be applied to an electrified light duty fleet, biofuels are currently the only available renewable, low-carbon option for air travel, long distance, and heavy-duty transport that does not require substantial infrastructure change. The prospect of large-scale biofuel production has prompted concern regarding long-term sustainability and contributed to a broad discussion over the appropriate uses of various biomass feedstocks (*5*). The choice of which plants to use as biomass feedstocks, and which fuels to produce from biomass in order to support these larger objectives, must fit into one of the ultimate goals of sustainability (*6*) – balancing the needs of the current generation with those of future generations as shown in Table I.

Table I. Goals of sustainable biofuel development

Increase standard of living worldwide	*Decrease Environmental Impact*
Maintain or improve energy efficiency	Minimize energy and material extraction
Increase reliable access to affordable energy	Net GHG benefits based on full lifecycle accounting
Maintain or increase nutritional food supply and distribution	Minimize conversion of undeveloped land
Maintain or improve potable water access	Sustainable water and nutrient use
Improve economic conditions	Minimize loss of biodiversity

While there is a subset of stakeholders directly involved in the biofuels value chain (production and consumption), in some sense, every person on the planet is a stakeholder in biofuels. All humans use energy in one form or another and, in the context of an increasingly integrated global economy, most humans rely on transportation fuels either directly or for the food and other material goods they consume. Also, most humans have some interest, whether direct or indirect, in the sustainable functioning of the planet, its ecosystems, and human industry, which includes sustainability of transportation fuels.

As depicted in Figure 1, a large number of intersecting concerns have emerged regarding expansion of the biofuels industry. How stakeholders prioritize these issues, combined with interactions among stakeholder groups, influences choices that govern if and how the biofuels industry will develop in the coming decades. The critical choices surrounding of biomass feedstocks epitomize the broader debate around biofuels and serves as a good model for better understanding the complex interactions that will govern development.

The emergence of first-generation biofuels was tied to conventional agricultural products that were locally and abundantly available. An examination of the history of biofuels indicates the important roles played by numerous interconnected and regionally variable social and economic circumstances. The price and availability of fuel, especially in times of political conflict, the state of agricultural activity, and the cost of conversion to fuels seem to be main driving factors. Initial traction for biofuels from various feedstocks centered around the desire for energy security and independence and the support of local agriculture. As public perceptions underlying these drivers have changed, and new drivers such as concern about sustainability have emerged, there has been increased scrutiny regarding the acceptability of certain feedstocks for biofuel.

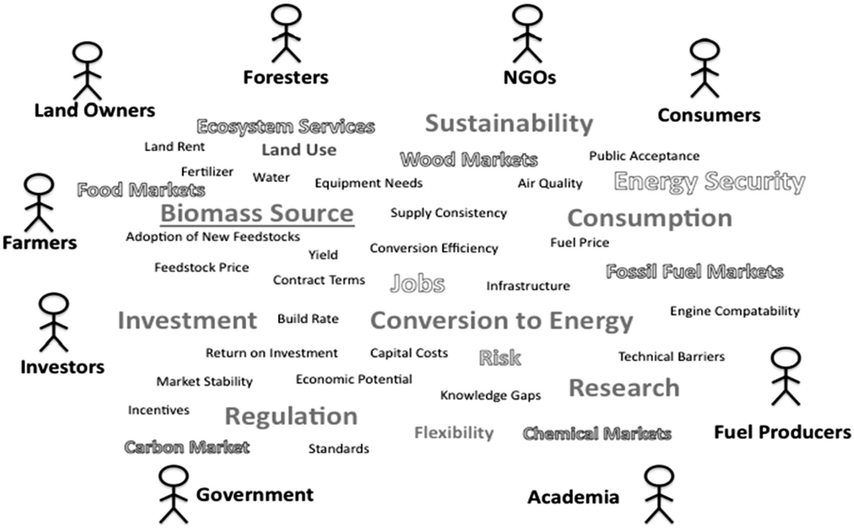

Figure 1. Stakeholders and values related to biomass feedstocks choices.

First-generation, or conventional biofuel, feedstocks include: (1) sucrose from sources such as sugarcane or sugarbeets or starches from grains such as corn or wheat, from which ethanol is made; and (2) plant oils derived from sources such as the seeds of palm, soybean, and rapeseed/canola, from which biodiesel is be made. The fractions of commodity crops used to produce biofuels and food, feed, and fiber worldwide in 2009 are shown in Figures 2 and 3. Since these conventional feedstocks are also food and animal feed, using large quantities for fuel presents potential long-term sustainability conflicts.

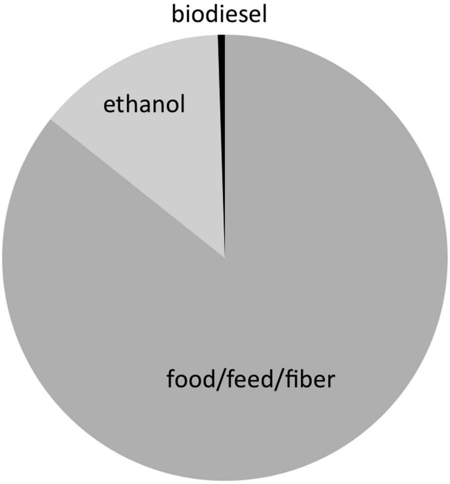

Figure 2. Worldwide use of major commodity crops in 2009 (7).

The production of food is resource intensive. Typically, only a small, highly nutrient-rich portion of the plant is used as food or feed (e.g. fruit, nuts, seeds and seed grains or sap in the case of sugarcane). Thus, a small portion of the photosynthetic capacity of the plant is captured for use. In the case of conventional biofuels, even more of the energy is lost through conversion into a secondary energy carrier such as a liquid fuel. Currently less than 15% of the crops currently processed for food and feed go to biofuel production. Many argue that expanding use of these feedstocks should be approached with caution and that development of new feedstocks that do not compete with resources for food production is more appropriate.

The prospect of using the whole plant (stems, leaves, and other inedible parts of the plant such as husks and hulls), through conversion of the lignocellulosic material has obvious potential to increase the energy recovery in a way that does not compete with food production. Each year, billions of tons of lignocellulosic biomass are generated globally (*8–11*). A great proportion of this material is left behind during agricultural activities, forest maintenance, and other human activities, is burned or land-filled. There is an opportunity to use some of this residual biomass for energy production. In addition, there is an opportunity to develop new, purpose-grown crops for bioenergy that could utilize lands not suitable for food production (*12*). Although, these next-generation biofuel feedstocks require additional technology and infrastructure to develop, they offer the potential to greatly expand biofuel production to levels that could decrease our reliance on fossil fuels. Which feedstocks are chosen for the next generation of biofuels depends on the complex interactions of stakeholders and their various value systems.

There are many players along the biofuels value chain that impact biomass feedstock choices. The simultaneous evolution of two main interdependent groups of primary stakeholders, biomass producers and biofuel producers/biomass consumers) is central to biofuel production. This development is influenced by other, external stakeholders (policymakers, NGOs, researchers, investors, and the public ((*13*), and references therein). Understanding the context of biofuels from conventional feedstocks is required to frame the stakeholder viewpoints moving forward as new biofuel pathways and feedstocks enter the highly charged arenas of social, political and economic debate.

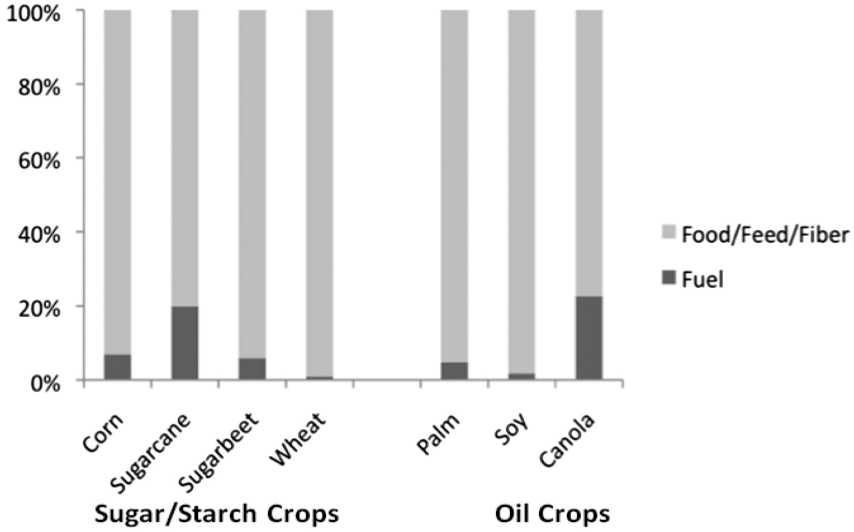

Figure 3. Worldwide use of major biofuel crops for fuel, feed and fiber in 2009 (7).

Conventional Biofuel Feedstocks

Corn Ethanol in the United States

In the U.S., interest in biofuels began with widespread use of personal automobiles. Both Henry Ford and Rudolph Diesel were proponents, but the cheap price of petroleum derivatives allowed fossil fuels to dominate the transportation fuel market. Biofuels resurfaced in the context of energy security in the 1970's. When price volatility and embargoes spurred fuel shortages, the nation turned to the productive corn farmers of the Midwest, subsidizing production of homegrown ethanol for blending with gasoline.

The push for corn ethanol was short-lived, fading quickly with falling oil prices during the economic boom of the 1980s and political changes in many oil producing countries. Interest rebounded in the 1990s – blending of ethanol had the added benefit of anti-knock properties and could replace tetraethyl lead as a combustion facilitator, reducing smog formation. The Clean Air Act Amendments of 1990 (*14*) required reformulated gasoline to contain at least 2% oxygen by weight. The Winter Oxyfuel Program (1992) required 2.7% oxygen in cold months for cities with elevated carbon monoxide with ethanol as the common oxygenate. The Year-Round Reformulated Gasoline Program

(1995) required 2% oxygen. MTBE (methyl-tert-butyl ether) and ethanol were the cheapest oxygenates and both were widely used. Ethanol was popular in the farming states of the Midwest, while MTBE was used elsewhere in the country. At its peak use, MTBE represented 87% of reformulated gasoline oxygenate (*15*) then studies in the mid to late 1990s showed MTBE was not only toxic, it moved easily into water systems exacerbating contamination events (*16–18*). California, the largest user of MTBE at the time, was the first state to ban the compound in 2003. With other states following suit and ethanol as the only economically viable replacement, a new corn ethanol boom began. The Energy Policy Act of 2005 established the first renewable fuel standard, mandating the use of ethanol in gasoline.

The growth of corn ethanol in the U.S. has always been a source of controversy. The industry has had a definite positive economic impact on rural farm communities and contributed to investments in yield improvements. Industry critics often like to shock the public by stating that as much as 40% of the acreage to produce corn is being used for ethanol. This, however, is a very misleading statement. It implies farmers are shifting from food to fuel production (hence the “food versus fuel” debate). While it is true that a large acreage is being used for corn ethanol, the actual production of corn for food and feed (domestic and exported) has not been reduced. The U.S. produced 13.2 billion bushels of corn in 2009, a new record - up from 9.5 billion bushels in 2001 (Figure 4). Feed corn and residual use has fluctuated between 5 and 6 billion bushels per year from 1992 to 2009 and exports have remained steady at around 2 billion bushels per year (*19*) (Figure 4). In 2009, 42.5% of corn was used for feed, 32.1% for ethanol, 15.7% for exports, 3.5% for high-fructose corn syrup, and 6.2% went to other uses (starch, sweeteners, cereal, beverage alcohol and seed) (*20*).

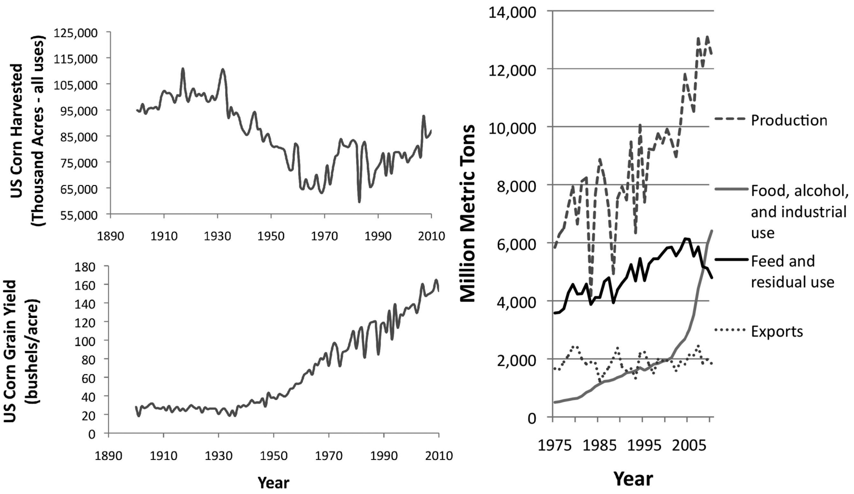

Figure 4. U.S. Corn grain yield (upper left), harvest corn acres (lower left) and uses (right) (19).

As a result of improved productivity and some redistribution of acreage, the U.S. expanded corn production to meet the ethanol blending market. The yield per acre has risen with a fairly constant trend, increasing 1.6 bushels per acre per year. Whereas an acre of U.S. farmland produced an average 138.2 bushels in 2001, the average yield was 152.8 bushels per acre in 2010. The number of corn acres also increased from roughly 75 million in 2001 (a low point in the trend) to 88 million acres in 2010 (a return to the acreage used for corn production in 1948) (*19*). Total farmed acres in the U.S. have remained flat at around 240 million acres for the eight major crops (corn, sorghum, barley, oats, wheat, rice, cotton, and soy) (*7*).

Increased corn production was not without impacts. The ethanol boom of the mid-2000s coincided with rising oil prices, which negatively impacted all agricultural production, including corn, causing food prices to rise. Petroleum prices affect the cost of activities on the farm (planting, field maintenance, and harvesting) as well as fertilizer prices and, of course, transportation from farms to feedlots, food processors, and consumers. Conditions incited speculation in commodity markets including general agricultural markets and corn ethanol. The outcome was a substantial rise in food prices which many blamed directly on the corn ethanol mandate. John Baffes and Tasso Haniotis at The World Bank Development Prospect Group stated "We conclude that a stronger link between energy and non-energy commodity prices is likely to have been the dominant influence on developments in commodity, and especially food, markets….We also conclude that the effect of biofuels on food prices has not been as large as originally thought, but that the use of commodities by investment funds may have been partly responsible for the 2007/08 spike" ((*21*),p2). While the actual contribution of corn ethanol versus oil prices and market speculation are difficult to sort out, the clear potential for a negative impact of food-based biofuels was sobering. Meanwhile, increasing use of fertilizers in the Midwest, of which corn cultivation is a major contributing factor, had caused the formation of an anoxic "dead-zone" at the mouth of the Mississippi River in the Gulf of Mexico. This anoxic plume was caused by the increased oxygen demand of growing microbial organisms, which was induced by increased nitrogen availability from fertilizer runoff in the enormous Mississippi watershed during the summer months. Between 1980 and 2000, the hypoxic zone nearly doubled (*22*). Concern over environmental impacts of corn ethanol, and greenhouse gas levels in particular, prompted the U.S. Congress to place a 15 billion gallons per year (57 billon liters per year) limit on the volume of corn ethanol production that can qualify as renewable in the revised Renewable Fuel Standard (RFS2) (*23*).

Sugarcane Ethanol in Brazil

Similar to the U.S., Brazil implemented national programs to encourage biofuel production and use. Brazil had a large sugarcane industry and could easily produce raw sugars for conversion to ethanol, a much simpler process than producing ethanol from cornstarch. Although sugarcane ethanol had been blended at 5% into gasoline in Brazil since the 1930's (*24*), the industry did not really take off until the 1970's in response to high oil prices. The Brazilian government began the Proalcool program in 1975 (*25*). The program was expanded in the subsequent decades through controlled economic manipulation of the domestic fuel market in Brazil. In 1983, Petrobras, Brazil’s largest oil producer, took control of ethanol blending at the pump. The company, created in 1953 (*26*), is majority owned by the Brazilian government and had a legal monopoly in Brazil until 1997 (*27*). To force adoption, the government set gasoline prices at twice the U.S. price while Petrobras sold ethanol at a discount, 20-60% below the price of gasoline (*28*).

In the late 1980’s, rising prices in the sugar market caused a drop in ethanol production which coincided with falling oil prices. As in the U.S., the Brazilian ethanol industry slowed, only to be revived through policy efforts. In 1993, a 20% blend requirement was instituted (*29*). In the early 2000’s, reforms to address sugar price volatility and the implementation of a flex-fuel car program prompted further expansion of sugarcane ethanol production. Climate goals caused the government to implement the National Agro-Energy Plan of 2005 (*30*), which called for expansion of biofuels. In 2010, the industry produced 36 million tonnes of sugar (exporting 28 million tons) and 29 billion liters of ethanol (*31*).

This increase in sugar ethanol production coincided with deforestation activity in the Amazon, leaving some stakeholders with the impression that biofuels were to blame. Sugarcane acreage and per acre yield did increase during the ethanol boom, as did acreage in soybean, feed corn, and cattle pasture. Brazil’s total territory spans 850 million hectares, of which roughly 550 million hectares are suitable for crops and grazing (not forested). Cattle occupy 200 million hectares, while soybean and corn occupy 30 million hectares and 8 million hectares are planted in sugarcane. Cattle density is extremely low in Brazil. Estimated stocking density in Brazil averages 1 animal per hectare. In 2001, sample tabulations indicated that 40% of pasture had a cattle density in of 0.5 animals per hectare (*32*). Cattle grazing has been implicated in primary deforestation activities, as way to establish land tenure which is important in the context of weak land titling (*32*, *33*). Conversion of pastures to soy in regions near the Amazon is speculated to contribute to movement of the pasture frontier into forested regions by displacing grazing (*34*).

Most sugarcane is grown in the Southeast, and the main sugarcane producing regions are about 2,000 kilometers from the Amazon rainforest. However, many are concerned that conversion of lands to sugarcane could push other agricultural activities, such as cattle ranching, into sensitive ecosystems (*35*). These concerns prompted the Brazilian government to seriously evaluate land use potentials. The result was an unprecedented national agroecological zoning plan (*36*), which concluded that an additional 55 million hectares could be available for responsible sugarcane expansion through cattle intensification. While sugarcane ethanol proponents argue that such planning, along with other protections such as the establishment of legal reserves and amendments to the Forest Code will protect sensitive ecosystems, NGOs and watch-dog agencies doubt these “paper protections” will survive political manipulation or be enforced.

These negative views are strongly countered with the positive effects that sugarcane ethanol production in Brazil may have with regard to greenhouse gas emissions, which includes emissions from fuel and fertilizer use and soil disturbance. With a more than 60% reduction in greenhouse gas emissions compared to conventional gasoline, Brazilian sugarcane ethanol is the only first-generation biofuel that will qualify as an advanced biofuel under the U.S. revised Renewable Fuel Standard.

Biodiesel in Europe

Europe is the biggest biodiesel market in the world. Where gasoline dominates the domestic markets in the U.S. and Brazil, diesel fuel garners the larger share in Europe. Although all three regions use and support biodiesel, programs in the E.U. far exceed those in the U.S. and Brazil.

Finding appropriate feedstocks for biodiesel production has proven to be much more challenging than for ethanol. The first uses of European biodiesel were in France in the 1900s. Rudolf Diesel demonstrated his engine at the 1900 World's Fair in Paris and the Otto Company began manufacturing engines. Both used peanut oil, which was available from French colonies in Africa (*37*). Research into biodiesel was conducted in many European countries in the 1930's but, like ethanol, the cheap availability of petroleum distillates prevented further development. Fuel shortages during World War II caused many countries in South America, Africa, and Asia to turn to biodiesel from local oilseed sources; however, the Germans opted for a coal-to-diesel gasification route instead. In these early implementations, straight vegetable oil was used, often mixed with some diesel. It would not be until the fuel shortages of the late 1970's and early 1980's that Europe would begin investing in modern biodiesel, with the real expansion in biodiesel production beginning in the decade between the mid-1990's to mid-2000's.

Biofuel production and use was embraced differently by individual European countries. Austria and France were early adopters. Germany did not begin commercial production until 1995 (*38*). In 2003, reforms to the Common Agricultural Policy (CAP) (*39*) were passed, adjusting trade balance issues for agricultural commodities and incentivizing energy crops. The European Commission established a goal of deriving 2% of transportation fuels from biomass by 2005 and 5.75% by 2010. Farmers were offered incentives and restrictions to grow energy crops (*40*). By 2004, the E.U. was producing 2.3 billion liters per year of biodiesel, 80% of total European biofuel production, mainly from rapeseed oil. Germany, France and Italy were the top producers. Despite this, the E.U. fell short of its goals, with renewables representing only 1.4% of total transportation fuels in 2005 (*40*). Land use was of concern even in these early days and farmers were required to set aside 10% of their land to receive CAP payments (*40*). Limitations in local production capacity spurred imports of soy and palm oil in some E.U. nations.

The wide variation in availability of oils has a substantial influence on feedstock choices for conventional biodiesel production. As shown in Figure 5, whereas the U.S. and Brazil rely heavily on soybean oil for biodiesel production, rapeseed (canola) is the feedstock of choice in European countries.

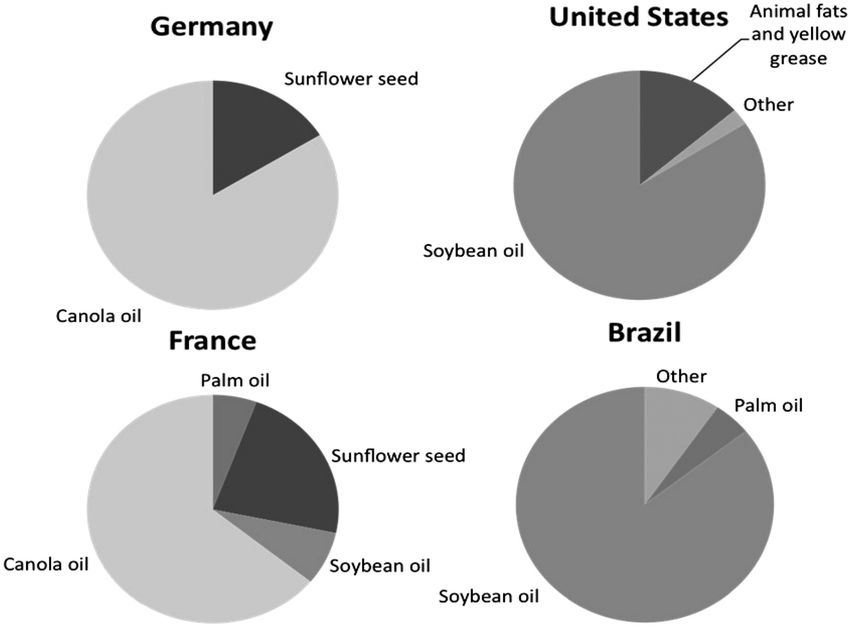

Figure 5. Choice of feedstocks for biodiesel production in various countries (43).

Oil palm is the highest producer of oil per unit land at 1500-2300 liters per hectare vs. 460 liters per hectare for rapeseed and 175 liters per hectare for soybean (*41*). In 2009, the E.U. in aggregate was the largest importer of palm oil, while the top three single-country importers were China (6.6 billion tonnes), India (6.1 billion tonnes), and the Netherlands (2 billion tonnes) (*42*). Palm grows in a very limited range, only 10-15 degrees from the equator. In 2009 Indonesia and Malaysia produced 45 billion tonnes, 85% of the world's palm oil (*42*). The importation of palm oil to meet European biofuels targets has been highly controversial. Palm oil can be produced roughly 22% cheaper than European rapeseed (*44*). Some European governments have restrictions on the use of palm oil for biodiesel, siting concerns around deforestation and carbon emissions. Analysts are divided over whether these restrictions truly reflect concern over land-use change and response to NGO concerns about sustainability or whether they are simply a device to protect domestic production of oil crops within the E.U..

Environmental NGO's have polarized the issue, emphasizing cases of poor practice in biofuel production especially in the case of palm biodiesel (*45*). While there have been cases of expansion of palm plantations into native rainforests or peatlands with negative effects in some regions, palm has successfully replaced defunct rubber production in other regions with positive environmental benefits (*46*). Further, while many NGOs attribute expansion of oil production solely to biofuel policy, there has also been a concomitant increase in demand of oils for food, especially in China and India. In fact, production of all commodity oils has expanded in the last decade. Palm oil increased by 305% between 2002 and 2009. Interestingly, total palm oil used for biofuel represented only 7% of this increase or 5% of total palm oil production in 2009 (*7*, *47*). Likewise, soy and rapeseed production increased 204% and 322% respectively, with oil used for biofuel representing 35% and 33% of this increase or 18% and 23% of total oil production in 2009, respectively. Production of all other bio-oils increased 225% with biofuel production accounting for 1% of the increase and 0.7% of total oil production in 2009 (*7*, *47*). Thus, while demand for oils for fuel may contribute to increasing production, it is far from the only driving factor.

To address the economic and environmental concerns surrounding biodiesel adoption in the E.U., the European Commission and E.U. Parliament, as well as individual member countries, are working to develop sustainability metrics and regulatory policies that will complement renewable energy efforts (*48*). Organizations such as the Roundtable on Sustainable Palm Oil, an international, multi-stakeholder NGO supported by groups such as Friends of the Earth (*45*) and including businesses and environmental groups, can foster interactions that are key to the adoption of sustainability standards (see below). It is interesting that there has not been proportional controversy regarding the other biodiesel feedstocks such as rapeseed and soy. In fact, palm may be the first biofuel feedstock that will drive change in practice that will directly impact how a food product is made.

Next-Generation Feedstocks

In all three major cases of conventional biofuel implementation, U.S. corn ethanol, Brazilian sugarcane ethanol, and European biodiesel, there was a typical pattern of development. First, an existing crop could be used to produce the fuel molecule, with subsidized development of technology. A boom period ensued, followed by a predictable bust and slower growth. As with many such cycles, there was some economic chaos before the dust settled, causing some stakeholders to panic and draw dire predictions regarding the influence of biofuels on agricultural markets and harsh criticism of economic incentives for biofuel development. At the same time, scaling up of industrial agriculture to meet demand in other sectors also occurred, resulting in questions about environmental impacts and causing some stakeholders to panic and draw ominous correlative predictions. Fears about environmental and social impacts, mainly related to feedstock production, created a cautious atmosphere for development of next-generation biofuel feedstocks. As a result, candidate next-generation feedstocks are being held to an extremely high performance standard. The expectation is that they must compete well economically, result in improved environmental impacts relative to fossil fuel sources, and perform better than current agricultural activities.

New feedstocks for biofuel production fall into two broad categories: waste or residual biomass (biomass that is a byproduct of other activities) and dedicated energy crops (crops specifically grown for energy production). Stakeholders along the biofuels value chain have important roles in choosing the next-generation of feedstocks. The appropriateness of a given feedstock depends upon location and a number of physical, social and economic factors that influence stakeholder perceptions. None of these is without controversy. Each feedstock type has advantages and disadvantages that will be factored differently by various stakeholders and the interactions between stakeholders.

Residual Biomass: Agricultural, Forest, and Municipal Waste

Residual biomass can be derived from a wide variety of activities. The largest volumes come from three main sources: agricultural residues, forest residues, and municipal residues. Agricultural residues are lignocellulosic materials produced as waste products of food production including the stalks and leaves of corn (stover), wheat straw, rice hulls, nut shells, orchard and vineyard prunings, leftover stalks of sugarcane after crushing (bagasse), and myriad other products. The production of biomass by conventional crops varies substantially. While corn in the U.S. and Canada typically produces 3-6 Mg (metric tons) residual biomass per hectare per year, sugarcane production yields approximately 20 Mg bagasse per hectare per year (*12*).

While a large volume of this material is technically available (*8*), whether harvest is economically viable and environmentally advisable has not yet been determined. Currently only 6% of corn stover is harvested for animal feed and bedding (*49*). Collection of agricultural residues requires additional labor, time, and equipment which affects decisions regarding their uses as a bioenergy feedstocks (*50*). A survey of corn farmers in Iowa indicated that only 17% would be willing to provide corn stover for bioenergy use, with 37% undecided on the issue (*51*). Uncertainty surrounding equipment needs and environmental concerns, especially possible effects on soil erosion and quality, were considered a barrier. More than four in five (84%) respondents thought they would need custom baling to achieve stover harvest and 78% felt removal of 50% of stover would decrease soil nutrients.

Assessment of available forest residues is similarly fraught with issues. Roughly one in six pulp and paper mills has closed since the 1990s (*52*). As a result, forests in North America have been accumulating biomass with an almost 10% increase in growing stock from 1990 to 2010 (*53*). Although an impressive amount of residual biomass is generated during activities such as logging and forest management in the U.S. each year, collection of forest thinnings and slash (treetops, branches and other materials typically left behind during logging for higher value timber and pulp logs) can be technically and economically challenging. This diffuse material requires additional equipment such as on-site chippers or bundlers as well as additional time, labor, and trucking capacity to handle and transport materials (*54*). Roughly 87 million dry tons of wood residues were generated at processing facilities in the U.S. in 2007 (*55*). While woody residues produced during milling were once considered a cheap and reliable source of bioenergy material, the use of secondary residuals in composite materials have all but eliminated this supply in many areas of the country. The Forest Service estimates that only 40% of residues were used for energy production (heat and electricity) while 55% of residues were used as fiber and other products such as bedding and fillers (*55*).

Currently some of the residual biomass material generated in agriculture and timber harvest is landfilled or burned. Use of such material for fuel production has obvious environmental benefits. However, some residual biomass, such as corn stover, is incorporated into the soil, returning carbon and nutrients; thus, the sustainability of removing some or all of this material has been questioned. Similarly, forest residues, which include thinnings and slash from forest harvest and maintenance, may provide nutrients to soil and habitats for smaller organisms; thus, removal may have some negative impacts (*56*). Engagement of farmers and foresters is needed to understand technical, ecological, and socioeconomic factors that might limit or enable availability of these feedstocks. Although research is underway to determine the extent of long-term sustainable removal of residues from fields and forest, it is likely this will vary for different feedstocks and by soil type, biome, and other local conditions.

Municipal biomass residues include food waste, paper, cardboard and packaging waste, used lumber and demolition wood, yard waste, and urban tree trimmings. In 2009, these biogenic materials represented 62% of the 243 million tons of municipal waste generated in the U.S. before recycling (*57*). While the recovery of energy from waste biomass has been embraced in countries with limited landfill capacity, notably E.U. members and Japan, adoption has been stalled in the U.S. for a number of stakeholder-related issues (*58*). First is the perception that energy from waste will create markets for an unsustainable biomass source, impeding efforts to reduce waste, and reuse and recycle materials. This is largely refuted by the continuing increase in both waste reduction and recycling in E.U. nations that have substantial waste-to-energy programs and zero land-fill policies (*59*). The second perception is that waste-to-energy has negative environmental impacts. This perception is largely based on outdated views of turn-of-the-century mass-burn incineration units (*60*). A wide range of improved technologies are being deployed to convert organic municipal waste to fuels, heat, and electricity with low emissions (*58*, *61*). Like any technology, these systems need to be closely evaluated to ensure environmental compliance and conformance to desired lifecycle outcomes.

Dedicated Feedstocks: Perennial Grasses, Coppice Trees, and Non-Traditional Crops

Dedicated next-generation feedstocks are plants specifically cultivated for energy or fuel production. First-generation biofuel feedstocks are typically storage compounds produced during developmentally regulated ripening processes: seed starch in the case of corn grain, seed oil in the case of soybean, and storage sucrose in the case of sugarcane. In contrast, next-generation biofuel processes utilize the structural molecules that comprise the body of the plant. This allows use of the whole plant and allows harvest to occur over a wide time frame. Many of the feedstocks being considered for next-generation biofuel production are perennial in nature, which allows removal of the aboveground biomass while leaving the root structures in place to regenerate without replanting. By doing this, soil disturbance is reduced since the need for annual tilling and planting is obviated.

This results in substantial soil carbon accumulation. Harvest occurs on a rotation ranging from one to five years and in many cases can be delayed or managed to accommodate the needs of the fuel processor. Thus, some dedicated feedstocks could provide substantial ecosystem services as land cover between harvests.

In terms of biomass productivity, it is clear that dedicated energy crops can produce substantial biomass per acre and are often suited to lands not currently used for crop production (*12*). Switchgrass (*Panicum virgatum*) and other native prairie grasses, such as big bluestem (*Andropogon gerardii*) and Indian grass (*Sorghastrum nutans*), are well-suited to the dryer grassland prairies in the West, where wheat and corn productivity falls off without irrigation. These grasses are also productive in the central eastern grasslands of Tennessee and Kentucky which have largely fallen out of agricultural use (*8*, *62*, *63*). Similarly, *Miscanthus* (*x. giganteus*) productivity is well suited to areas in the southern Midwest and southeastern U.S., south of the regions of highest corn production (*12*, *64*), while tropical grasses such as Napier grass (*Pennisetum purpureum*) and energycanes (*Saccharum* sp.) are productive along the Gulf Coast (*65*).

If energy crops are embraced, an emerging consensus suggests such crops should be adapted to soils currently not suitable for crop or timber production, including salt affected (saline), acid/alkaline, arid, and flood-prone lands. For example, the perennials prairie cordgrass (*Spartina pectinata*) and reed canarygrass (*Phalaris arundinaceae*) and fast-growing trees such as *Eucalyptus* spp. are tolerant of water-logged and saline soils (*66*, *67*). Succulents such as *Agave* spp. (*68–70*) and other drought-tolerant and water efficient plants such as *Eucalyptus* are being investigated for semi-arid soils (*71–73*). Some short rotation woody species have potential in remediation. Willow (*Salix* spp.) can tolerate and accumulate heavy metals and may have application at abandoned mining sites and other contaminated lands (*74*). Both willow and short-rotation poplar (*Populus* spp.) may have applications in remediating treated wastewater (*75*, *76*). The development of novel feedstocks could have multiple benefits and provide the opportunity to implement renewable fuels in better and more sustainable ways.

The Stakeholders in Biofuels

Since the early days of corn ethanol, the variation among value sets when coupled to the highly charged political and economic interactions between biofuels and food production have created a challenging landscape for farmers, fuel producers, consumers, environmental advocates, and policy makers. In extremely general terms, stakeholder views about bioenergy feedstocks revolve around two wide-ranging core axis points – perceived economic effects (including everything from the price of energy and food to the functioning of entire rural economies), and perceived environmental effects (including greenhouse gas mitigation, soil and water quality, and ecosystem impacts). These axes are, of course, critical to the goal of balancing social, economic, and environmental sustainability across sectors, scales (local, regional, national, and global), and time (balancing the needs of current generations against those of future generations).

A generalized ranking of values by various stakeholders in bioenergy is illustrated in Table II. Such typifications should not be reified. Sweeping generalizations of stakeholders and broadly categorized stakeholder groups are inadequate for understanding the complex behavior of individual actors. Each individual or entity may belong to multiple stakeholder groups. For instance, an individual can be a farmer, landowner, investor, environmentalist and, of course, consumer. Prioritization of stakeholder values is a complex and evolving landscape influenced by various cultural and social inputs, past experience, location, interactions within and outside the stakeholder groups, and many other factors. The generalizations made here are offered as a convenient tool to aid understanding of general trends in value prioritization. As with any use of generalizations, a fuller and more variable spectrum exists – the reader is cautioned to make her/his own extrapolations in the absence of specific data.

Biomass Feedstock Producers: Farmers, Foresters, and Landholders

In some sense, feedstock choice begins with the feedstock producers. Most farmers make decisions regarding uses of their land for growing stock on an annual basis, weighing prices, previous practice, local markets, distributer preferences, prior experiences, and a variety of other factors. The price of land has substantial effects on availability of land for and cost of crop production and thus, crop pricing. While 84-96% of farmers in the U.S. own some of the land they farm, roughly 395 million acres of the 938 million acres of farmed land in the U.S. is leased, most often from non-farming landowners (*77*). Landowners typically have an interest in what is grown on their land and how the land is managed to ensure their land value is not degraded.

The perennial nature of most next-generation feedstocks currently under exploration for bioenergy production has both advantages and disadvantages for the grower. While a perennial crop typically has a higher cost of establishment (seeding/planting), this operation is needed only once over the lifetime of the crop and can be amortized over many years, in contrast to the annual cost of production associated with traditional row crops. However, the high cost of establishment may require additional credit availability and is a perceived barrier to adoption.

The harvest cycle can be variable for different feedstocks. For example, perennial grasses can be harvested yearly but woody species are typically grown on longer cycles, 3-5 years for coppice and up to 5-20 for conventional woody systems. This means the farmer must be able and willing to forgo annual return during the initial period.

Finally, access to specialized equipment for planting or harvest may be perceived as a barrier. These issues are not new to agriculture or forestry; economic models have been developed to understand factors affecting the change in acreage from annual row crops to perennial crops such as fruit, coffee, and asparagus (*78*, *79*).

Table II. Qualitative relative generalization of importance of values/concerns in various stakeholder groups

	Land Owner	*Biomass Producer*	*Fuel Producer*	*Consumer*	*Policy Maker*	*Environmentalist NGO*	*Scientist/ Engineer*	*Investor*
Personal Experience	••	••	•••	••	••	••	••	••
Profit	•••	•••	•••					•••
Crop Yield	•	•••	•			•	••	•
Conversion Efficiency			••••				••	•
Land Rent	••••	•	•		•			•
Equipment Needs		•	••				•	•
Labor		••	••	••	•••	•		
Tax Credits/ Incentives	•	••	••	••	•••	•		•
Delivered Feedstock Price	•	••••	•		•	•		•
Delivered Fuel Price			••••	••••	•••	•		•
Chemical Inputs	•	••	••		•	•••	•	•
Flexibility		••	••	•	•		•	•
Contracts	•	•••	••		•			•
Sustainability/ Environ. Impacts	•	••		•••	••	••••	•	

	Land Owner	*Biomass Producer*	*Fuel Producer*	*Consumer*	*Policy Maker*	*Environmentalist NGO*	*Scientist/ Engineer*	*Investor*
Technical Barriers		•	••		•		••••	•
Knowledge Gaps					•		••••	•
Uncertainty and Variation/Risk	•	••	•••	•	••	•	•	•
Market Stability		••	••	•••	••••			•
Public Acceptance					••••	•		•
Policy Barriers/ Permitting Cost	•	•	••		••	••		•
Return on Investment	•	•	•••		•			••••
Capital Costs		•	••••		•		•	•
Supply Consistency		•	••	•••	••			•
Economic Potential		••	••	•	••••			•

Several studies have examined, through different lenses, the willingness of farmers and landowners to allocate some land to switchgrass or miscanthus for energy purposes ((*80*, *81*), and references therein). Smith et al. (2011) examined the preference of landowners willing to grow energy crops for perennial grasses versus short rotation woody coppice. Agricultural landowners were surveyed (each with holdings more than twenty acres in the lower Minnesota River Valley, an area predominately used for corn and soy cultivation) near two sites that would utilize the biomass for power – 548 landowners (over half) responded to the survey. Nearly three in four (72%) indicated a willingness to grow perennials at some profit (*78*). Only 7% would use prime land for energy crops; the remainder would target marginal lands. Almost half of landowners surveyed indicated that they would use land with poorer soils for grasses and sloped land for short-rotation coppice. The study also indicated that, in general, landowners were more positive toward grasses than woody crops and many recognized non-market services such as soil retention, wildlife habitat and hunting opportunities, with 1 in 6 (17%) willing to sustain an economic loss for such benefits. Finally, the survey indicated prioritized concern about access to equipment and loss of loan eligibility over possible financial assistance programs (*78*).

In the absence of a robust, existing market for certain types of biomass, contracts are likely to have a large influence on landholder decision making. Historically, most agricultural products have been bought and sold for immediate delivery (through “spot markets”), but a growing share of U.S. farm output is produced and sold under agricultural contracts that govern how and when commodities change hands. In 2008, contracts covered nearly 40 percent of the total value of agricultural production, up from 11 percent in 1969 (*82*). Production contracts (where the contractor owns the commodity and pays the farm operator to raise it) are widely used in livestock production, while marketing contracts (where the farmer retains ownership of the commodity but promises future delivery to the contractor) are used for many crops (*83*). Smith et al. (2011) found that, for dedicated bioenergy crop production, landowners were more willing to grow perennial crops under a contract “… in which the landowner would receive an annual payment for a 10 year easement; planting, maintenance, and harvest would be the responsibility of a contract service provider; and the landowner would be paid for biomass crop upon delivery.”

In theory, contracts serve to apportion risk between the biomass producer and the biofuel producer and are important for securing credit. It is partially for this reason that U.S. Department of Agriculture has supported biomass producers with financial incentives such as the Biomass Crop Assistance Program (BCAP) (*84*) and has mirrored the Department of Energy in establishing loan guarantee programs for biorefineries which are discussed below and elsewhere in this book.

Biomass Feedstock Consumers: Fuel Producers

There is much less data on the drivers behind the decisions of fuel producers. The two main drivers for feedstock choice among fuel producers appear to be: (1) fit to technology; and (2) economic availability. However, not all processes and feedstocks are a good match (Table III).

Table III. Matching feedstocks and products to appropriate conversion technologies

Lignocellulosic Feedstocks	*Food Waste*	*Green Herbaceous*	*PaperWaste*	*Dry Herbaceous*	*Woody*
(Examples)	*(peels, hulls)*	*(sugarcane, sorghum)*	*(cardboard, paper)*	*(corn stover, switchgrass)*	*(poplar, waste)*
Technologies					
Combustion	•	•	•••	•••	•••
Gasification/ Pyrolysis	•	•	•••	•••	•••
Fermentation	•	•••	•••	•••	•
Anaerobic Digestion	•••	•••	•	•	
Moisture Content	•••	•••	•	•	••
Ash Content	•••	•••	•	••	•

••• = high content or conversion efficiency.

• = low content or conversion efficiency.

Similarly, the produced fuel or energy product is dictated by the conversion process as shown in Table IV. There are several ways to get to a desired product from a particular feedstock, but the pairing of feedstock and technology needs to be carefully considered. An examination of fifteen companies that announced intentions to complete a true commercial-scale lignocellulosic fuel plant by 2015, listed in Table V, indicate the majority of first-generation lignocellulosic plants are, as of 2011, planning on using residual biomass of some sort.

As biomass supply chains and their associated economics continue to evolve, companies have tried to diversify their feedstock choices. Beyond the underlying economics, the acceptability of feedstocks and conversion technologies by other stakeholders comes into play. Opposition by NGOs or other public interest groups can change the attractiveness of locations and thus affect feedstock choices (see below). Likewise, support or lack of support for particular feedstocks through policy objectives may tip the scales for the fuel producer.

Capital costs are high and the economics of operating a lignocellulosic biofuel plant are challenged by the cost of feedstock transport and storage. Without additional pretreatment and densification, the reasonable transportation distance from field or storage to the processing facility is roughly 50 miles or less (*85*). This limitation tends to drive processing facilities toward smaller production volumes, counter to the economies of scale which would otherwise drive toward larger production volumes.

In the end, the availability of feedstock within the economical transportation distance will influence facility location and size, especially for the first generation of commercial plants. Thus, companies are actively shoring up their access to biomass feedstocks far in advance of breaking ground for their conversion facilities. Many of the projects in Table V are receiving help in establishing feedstock supplies through the federal Biomass Crop Assistance Program (BCAPs).

Most of the plants currently being planned range from 10-50 million gallons per year and will require 125-625 thousand tons of biomass per year. For example, one survey indicated that producers in the southeastern United States would be willing to convert about 75 acres per farm to an energy crop such as switchgrass (*80*). At 8 tons per acre (600 tons per farmer) and 80 gallons of cellulosic ethanol per ton of switchgrass, a 50 million gallon facility would require about 625,000 tons per year or 1,042 farmers. Ensuring the reliability and quality of the biomass supply is a central concern of these biofuel producers. Unlike the feedstocks for first-generation biofuels, most of the feedstocks for next-generation biofuels will not be produced for other purposes, and their supply will be limited. In the absence of a vibrant spot market, companies have two main mechanisms to reduce supply risk. They can enter into contracts with producers or they can form vertically integrated operations and produce their own feedstocks. Doing either offers the company the advantage of optimized coupling of feedstock and processing needs. At the same time, being locked into a particular feedstock source could be a disadvantage. Losing the flexibility to adjust to feedstock or process difficulties or the opportunity to take advantage of cheaper feedstocks could be costly.

Table IV. Identifying conversion pathways to achieve desired end-products

Energy Products	*Combustion*	*Gasification/ Pyrolysis & Catalysis*	*Fermentation*	*Anaerobic Digestion*
Alcohols		•••	•••	
Liq. Hydro-carbons		•••	[••]	
Methane			○○	•••
Other Gases		•••		
Electricity	•••	○○	○○	○○
Co-products	metals recovered in ash	metals recovered in ash, biochar	treated water for irrigation, fertilizer sludge, possible feed/ nutrients	treated water for irrigation, fertilizer sludge
Cost	Low to Medium	Very High	Medium to High	Low to High

••• = produced directly.
[••] = emerging technology.
○○ = can be produced through secondary process, for example, additional conversion of byproducts.

Table V. Estimated metrics for companies with publically announced plans to open commercial-scale cellulosic biofuel plants in the U.S. by 2015

Company	*Vol.[a] Mgal/yr*	*Feedstock Type*	*State*	*Feedstock Contracts*	*BCAP Assist*	*Other Federal*
Abengoa	23	straw, stover	KS	Yes	Yes	$132M DOE loan guarantee
BlueFire Renew.	19	Waste wood	MS	Yes	No	$88M DOE grant, $125M USDA LG[b]
Coskata	16	Variable/ woody	AL		No	$250M USDA LG offer
Dakota Spir.AgEn.	8	Wheat Straw	ND	Yes	No	
DuPont Danisco	25-50	Switchgrass corn cobs	TN	Yes	Yes	
Enerkem	10	Urban waste	MS	Yes	No	$80M USDA LG, $50M DOE grant
Fiberright	3.6	Urban waste, waste pulps	IA	Yes	No	$25M USDA loan guarantee
Fulcrum BioEnergy	10.5	Urban waste	NV	Yes	No	
Great River Energy	20	Wheat straw	ND			
IneosBIO	8	Citrus, ag., urban waste	FL		No	$75M USDA loan guarantee
Mascoma-Valero	40	Wood	MI	Yes	No	$80M DOE grant
POET-DSM	25	Corn cobs/ Stover	IA	Yes	Yes	$105M DOE LG[c]

Company	*Vol.*[a] *Mgal/yr*	*Feedstock Type*	*State*	*Feedstock Contracts*	*BCAP Assist*	*Other Federal*
RenTech-ClearFuels	20	Wood waste	TN	Yes	No	$23M DOE grant
Terrabon-Valero	20	Urban waste	TX	Yes	No	
Vercipia-BP Biofuels	36	Energycane bagasse	FL	Yes	No	
Zeachem	25	Poplar, ag. waste	OR	Yes	Yes	$232M USDA loan guarantee

[a] Data from various sources including press releases, company websites and industry publications. [b] LG=loan guarantee. All plants are slated to make ethanol with the exception of Gevo, producing biobutanol, and Terrabon, producing biogasoline. [c] Pending approval. [d] Award offer. The company has indicated they will forgo the offer in favor of private investments.

DuPont Danisco is planning a 25-50 million gallon per year facility in eastern Tennessee. Slated for completion in 2014, the company is partnering with the University of Tennessee Research Foundation's corporate venture Genera Energy LLC, which began contracting with farmers to produce switchgrass on thousands of acres in 2008 (*86*). Similarly, POET, a cellulosic ethanol company using corn cobs and stover, has been contracting with farmers to harvest and bale residual biomass. The company's planned plant in Iowa will consume nearly 300,000 tons of biomass per year. In 2010, farmers harvested 56 thousand tons of corn cobs and stover under contract with assistance from BCAP. POET's plant is set to begin operations in 2013.

Vertical integration, having total control over all phases of the business from feedstock production through conversion to fuel and fuel distribution, is one way to avoid costly interruptions in production. The degree to which advanced biofuel and cellulosic ethanol companies will vertically integrate remains unclear. While vertical integration is common in the sugarcane ethanol industry, models are more mixed in the corn ethanol and bioelectricity sectors (*87*). Companies taking on the role of harvest and storage include Abengoa Bioenergy, which is planning a commercial plant in Kansas to use wheat straw and corn stover. The company had contracted as much as 60% of their feedstock as of 2010. Using a satellite depot storage model, the company purchased agricultural in-field residues from the farmer after the grain harvest and performed the harvest, transportation, and storage functions themselves (*88*).

Another strategy is co-location, contracting, and or mutual investment with a single supplier. This seems to be especially successful for residual biomass. RenTech-ClearFuels has co-located their future commercial wood waste-to-jet/diesel fuel operation with a wood products manufacturing facility owned by Hughes Hardwood International in Tennessee and has negotiated a Memorandum of Understanding for the feedstock supply while the technology is further developed. To ensure supply to their 19 million gallon a year waste wood to ethanol plant in Fulton, Mississippi, BlueFire Renewable signed a 15-year contract with Cooper Marin & Timberlands, a company specializing in wood chips and other residual forest products. Similarly, Sachem has partnered with GreenWood Tree Farms to provide the bulk of their woody biomass and Fulcrum BioEnergy entered into a 15-year supply agreement with Nevada Waste Management to deliver sorted waste to their planned waste-to-ethanol plant. Terrabon invited Waste Management to invest in the company as well as supply feedstock to their urban waste-to-ethanol venture. Enerkem has co-located all of their projects with waste biomass producers. The planned 10 million gallon per year commercial waste-to- ethanol plant will be located in Pontotoc, Mississippi, near the Three Rivers Landfill. The model also works for dedicated feedstocks. Vercipia/BP Biofuels has contracted with the Lykes Brothers Farm in Florida to provide sugarcane/energycane for their bagasse-to-ethanol process.

Sometimes feedstock supply economics don't work out as planned. For example, Dakota Spirit AgEnergy discovered that the feedstock supply for their planned 20 million gallon per year wheat straw-to-ethanol plant in North Dakota was not feasible. The plant would have needed about 480 thousand tons of biomass per year. A detailed study indicated that only 192 thousand tons of corn stover and wheat straw could be reliably procured within 100 miles of the plant. As a result, the plant was reconfigured to produce 8 million gallons per year cellulosic ethanol and 50 million gallons per year first-generation corn ethanol. Slated for completion in 2014, harvest of two thousand acres corn stover and two thousand acres of wheat straw were trial harvested in 2011 (*89*).

Biomass Feedstock Governance: Policymakers, Governing Bodies, Non-Governmental Organizations, and the Public

This set of stakeholders is the most complex. As agents of the public, governing bodies, policymakers, and in some cases NGOs, have multiple roles, both as indirect stakeholders and as a key interaction point for other stakeholders. The dividing lines here may get a bit fuzzy. Is government really simply an extension of the public or does it function as a separate stakeholder? Is there a difference between a consumer and the general public? While it can be argued that a subset of the public directly consumes biofuels, the fact is that biofuels are integrated heavily with the general liquid fuel market which affects the general public directly through the price of transportation and indirectly through the price of nearly all consumer goods and services. Thus, almost all members of the public can be considered consumers in this context. Likewise, the government itself is a consumer. In fact, some of the largest contracts for advanced biofuels are through military contracts (*90*).

As can be seen by the historical development of first-generation biofuels, policymakers have implemented key drivers, and yet at the same time, key restraints in development of the industry. It is the special role of the policymaker to walk a thin line between forward-thinking optimism over the promise associated with new technologies and the doom-foreseeing caution of catastrophic outcomes that could accompany wide-spread deployment of new technology and infrastructure. In this regard, policymakers try to balance the values of NGOs and environmentalists that desire the strictest possible regulations with the social and economic interests of relevant industry and consumer/public stakeholders. Thus, they must endeavor to protect the environment while encouraging economic growth and social well-being. This juxtaposition of values sometimes results in seemingly self-contradictory behavior on the part of government. Policymakers may support regulations that industry and economists view as stifling to biofuel development while at the same time supporting financial incentives to encourage biofuels (the special role of government as an investor is discussed in the section below).

Most governments are approaching the sustainability problem through performance standards, with major focus on greenhouse gas emissions and minor efforts in other areas of sustainability including biodiversity and water impacts (*91*), simultaneously supporting growth in the industry. For example, the U.S. Energy Independence and Security Act (EISA) and the Revised Renewable Fuel Standard (RFS2) have strict definitions for how feedstocks are defined as ‘renewable’ and restrict fuels derived from some feedstock from qualifying for tax incentives At the same time, USDA is offering financial assistance through BCAP for a defined subset of biomass feedstocks (*84*). The BCAP program, in particular, has had an effect on feedstock choice. Under the program, farmers receive reimbursement for up to 75 percent of establishment costs and maintenance payments for up to five years for herbaceous and up to 15 years for woody crops. As indicated in Table V, the program has contributed greatly to efforts to establish feedstock supply chains for the first commercial ethanol plants. For example, the USDA approved payments to Abengoa for establishment of 20,000 acres of switchgrass (the company requested funding for 50,000 acres), which would provide 15-20% of the plant's feedstock needs.

Government operates at multiple levels influencing different groups of stakeholders. In addition to federal programs, individual states have enacted policies that may affect biofuel feedstock choices. For example, California has enacted its own Low Carbon Fuel Standard (LCFS) which assesses transportation fuels including electricity and liquid fuels by a life-cycle analysis greenhouse gas reduction target. In all, the Center for Climate and Energy Solutions (formerly the Pew Center on Global Climate Change) reports 45 of 50 states with some combination of financial incentive, fuel standard, and fuel use requirement regarding alternative fuels such as ethanol or biodiesel, as well as eight different regional initiatives. Unfortunately, such efforts are not always aligned (*92*), which can create uncertainty for other stakeholders. Policy heterogeneities illustrate local effects and feedback relationships surrounding biomass and biofuel development, as well as the regional and political differences among public stakeholders.

The development of sustainability metrics, performance standards, and certification schemes specifically for biomass production has become a focused effort for governmental and non-governmental agencies alike (*84*, *91*, *93*). Following the lead of the organic farming movement and groups monitoring sustainable forestry such as the Sustainable Forestry Initiative and the Forest Stewardship Council, several industry and NGO-partnered multi-stakeholder groups have arisen to take on the challenge. The Sustainable Agriculture Network, the Better Sugarcane Initiative, the Roundtable on Sustainable Palm Oil, the Roundtable on Responsible Soy, the Sustainable Agriculture Network, and the Roundtable on Sustainable Biofuel (specifically addressing biomass for biofuels and bioenergy) are a few of the leading organizations in this effort (*94*, *95*). While it is hoped that the efforts to engage biofuels producers in supporting sustainability standards will spill over into other agricultural activities, the numbers are not wholly supportive of this effect yet. At the end of 2011, only 9% of world palm oil was certified sustainable by the Roundtable on Sustainable Palm Oil (*96*) despite widespread campaigns by NGOs (see discussion below regarding interactions between stakeholders).

NGO's have diversified roles as direct stakeholders, as watch-dogs of both progress and process, and as self-appointed representatives of so-called "silent stakeholders", which includes disenfranchised groups such as the poor, the uneducated, future generations, and non-human stakeholders (*97*). As such, NGO's can be powerful actors and wield influence through a number of interactions with other stakeholders as illustrated in Figure 6. The actual role of a particular organization in an area is often difficult to ascertain as NGOs can comprise a variety of stakeholder and non-stakeholder viewpoints and objectives.

Since these are typically non-transparent, it is really only through activities and interactions with other stakeholders that a role can be defined (see below).

Governments and NGOs also have roles in educating the public regarding technology, economic opportunities, and issues of health and safety. Education about bioenergy in general, and bioenergy feedstocks and sustainability in particular, has a large influence on public perception that will affect levels of adoption and feedstock choices. Even nations such as Finland, with a relatively large commitment to bioenergy, face the continued need for education in this area (*98*). Van de Veldt *et al.* (2011), found that there was both a real and perceived lack of information about biofuels and that consumers were generally wary of information coming directly from the fuel producers or the media. While government was a more trusted source of information than industry, scientists and NGOs were ranked highest for trustworthiness, honesty, and knowledge (*99*).

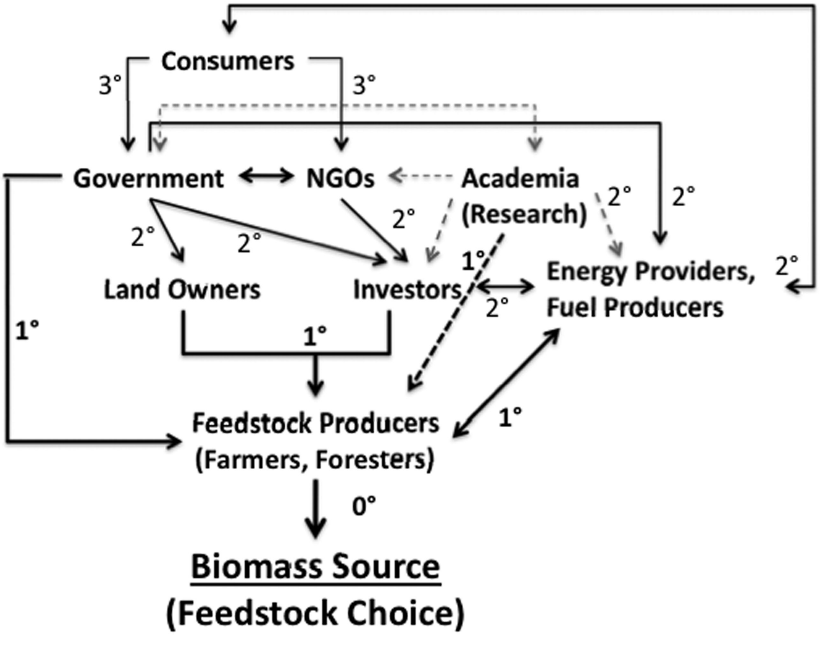

Figure 6. Map of stakeholder interactions that influence biomass feedstock choices. Primary interactions indicate a direct effect the stakeholder or direct influences such as contracts or regulations. Indirect interactions such as social, cultural, political, or influences through other stakeholders are indicated as secondary and tertiary to the actual feedstock choice.

The Special Roles of Researchers and Investors in Feedstock Choices

Investors play a crucial role in moving technology from the bench to commercial-scale production. While government can set policy targets, such as the Renewable Fuel Standard, if capital is limited, production will not occur as expected. This is exactly the situation facing lignocellulosic ethanol and many advanced biofuels. The hefty costs associated with building a first-generation plant ($300-$500 million dollars), risks of unproven technology, lack of established feedstock supply chains, a recent long-term economic downturn, and increased scrutiny on lenders have delayed commercial production. The result is clear – the expected volumes of lignocellulosic ethanol and advanced biofuel have not materialized and the targets set in the RFS2 have not been met. If all the plants listed in Table V were built and operating at capacity by 2015, the volume of lignocellulosic ethanol would be around 300 million gallons, or one-tenth of the 2015 target of 3 billion gallons. Until the first plants are up and running it seem unlikely that there will be widespread investment in the additional plants needed. Delay in construction of plants will put producers even farther behind in meeting the 2022 goals of 16 billion gallons of lignocellulosic ethanol.

As a result of this confluence of drags on the biofuel production system, the government has assumed a special role as investor and guarantor. The government is a direct investor in feedstock development through the BCAP program (*100*) and federal grants have provided start-up money for numerous next-generation biofuel projects. Historically, such grants are limited to assisting with pilot and demonstration-scale efforts; however, there has been some recent activity in grants to assist commercial-scale start-ups (Table V). DOE's Biomass Program, through the American Recovery and Reinvestment Act, invested over $700 million in biofuels and bioenergy (*101*). The award included $509 million for pilot and demonstration scale projects, $82 million for commercial-scale biorefinery projects, and $107 million for fundamental research with $5 million to fund sustainability research. Similar efforts to develop cellulosic fuels are underway in many other countries including European Union member states, China, and Brazil.

The US DOE and USDA have also recently launched loan guarantee programs to help bridge the gap in capital caused by the current economic situation. As shown in Table V, ten of fifteen companies reviewed here have taken advantage of grants or loan guarantees. It is likely these guarantees have catalyzed the prevalence of pre-build contracts for feedstocks and have had some effect on feedstock choice. It should be noted that all of the fuel companies relying on private investments also have feedstock contracts in place. Undoubtedly, the perceived attributes of feedstock availability and feedstock and conversion technology pairing are key factors in risk analyses by investors.

In this vein, both scientists and investors play a critical role in new technology development. They can provide honest assessments of technological promise through two different lenses; technical feasibility and economic or practical feasibility. Despite this critical role, these two stakeholder groups are often perceived to function at the periphery of technology adoption. Perhaps this is because they are both heavily involved in the initial stages of development but move to the background as a technology achieves market pull.

Unlike investors, scientists have an additional critical role in educating other stakeholders. For example, landowners may be aware of and supportive of the biofuel and bioenergy sectors, generally, but may lack information regarding new bioenergy crops and markets that affect their decisions regarding land-use for biomass production (*81*, *102*). Scientists also play key roles in informing Government and NGO's regarding the risks and benefits of new technologies. While Government and NGO's are primary conduits of scientific information to the public, both are subject to their own stakeholder biases. Scientists can provide an important function as an "honest broker" in these discussions but they themselves must better communicate directly with other stakeholders and be careful to avoid contamination by industrial or political interests (*103*).

The perceived lack of a unified view in the scientific community can cause anxiety among other stakeholder groups. The evaluation of indirect life-cycle impacts, such as indirect land-use change, is one example. While many scientists may agree that indirect effects are worthy of consideration, there is still widespread disagreement over the availability of data and suitable methodology to accurately assess indirect effects (*104–107*). When policy is in front of science, the perceived disharmony creates uncertainty which disproportionally affects various stakeholders. Uncertainty surrounding economic and market factors for renewable fuels will primarily affect investors, policy makers, fuel producers, and ultimately consumers. On the other hand, uncertainty as to the sustainability of particular biomass feedstocks will primarily affect biomass producers, landowners, policy makers, and NGOs.

The investment of government in bioenergy research is an important factor in resolving these uncertainties and countries with prioritized interest in bioenergy are stepping up to the plate. The United States is a prime example. The U.S. Department of Energy has expanded work beyond the National Renewable Energy Lab to create a network of multi-institutional bioenergy research centers including the Great Lakes Bioenergy Research Center, the Joint Bio-Energy Institute, and the Bio-Energy Science Center (*108*). The U.S. Department of Agriculture has expanded biomass and bioenergy related research at its various Agricultural Research Centers (*109*). Universities are expanding their programs in bioenergy and industry is partnering with universities to fund bioenergy research at an unprecedented scale. One example is the $500 million, ten year commitment by BP to fund the Energy Biosciences Institute, a partnership between the University of California – Berkeley, the University of Illinois – Urbana-Champaign, and the Lawrence Berkeley National Laboratory (*108*). Government agencies are further incentivizing these efforts through programs such as the USDA's $136 million dollar investment in five partnerships involving university research and integration with industry in 22 states (*110*).

Interactions Between and Among Stakeholders

The complicated interactions and influence among stakeholders in bioenergy feedstock selection are depicted in Figure 5. Primary interactions indicate a direct effect on feedstock choice by the stakeholder or direct influences such as contracts or regulations. Indirect interactions, such as social, cultural, political, or influences through other stakeholders, may be considered secondary and tertiary to the actual feedstock choice. For example, contracts represent tangible evidence of direct interactions between biomass producers and the biofuel producers/biomass

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

consumers; whereas, the successful siting of biofuel projects and partnerships provides evidence of direct and indirect actions between research, education, policymakers, and the public. These relationships can be difficult to dissect; however, the effect of interactions between stakeholders on decision-making in bioenergy feedstock production has been examined using a variety of models that examine economic and social factors including economic models (*111*, *112*), agent-based models (*113*), and multi-criteria analysis (*114*, *115*).

Interactions tend to be of two types, synergistic and antagonistic, to feedstock choice. When values of interacting stakeholders are similarly aligned, synergism arises to encourage adoption of a particular feedstock. An example might be the choice of switchgrass for cellulosic ethanol. The predominance of research in Tennessee on switchgrass, the needs of local landowners to diversify crops, education programs arising from research that informs farmers about the benefits, risks, and likely practices associated with switchgrass cultivation, award of federal incentives for biomass crop production that include switchgrass, a local government that values diversified agricultural production and renewable fuels, a federal government that has a fuel standard that includes switchgrass as a renewable feedstock, and a fuel producer willing to invest in technology involving conversion of switchgrass to fuel and willing to contract with farmers and/or the research center ***all*** contributed to the proposed DuPont/Danisco plant.

Alternatively, antagonism, arising through conflicts in stakeholder values might discourage a particular feedstock choice. The use of palm oil as a first-generation biodiesel feedstock is an iconic example which also highlights the web of influence exerted by NGOs. As mentioned previously, the push for renewable fuel in Europe resulted in increased demand for plant oils. Since many European nations had previous political relationships with countries that produced palm oil and since palm was the cheapest oil to produce and import (*116*) there seemed to be scientific and economic incentives to select palm oil as a biomass feedstock. However, the competing interests held by farmers, economists, and policymakers weighed toward rejection of this feedstock in favor of something produced locally, such as soybean in the U.S. and rapeseed in the E.U.. Add to this scrutiny over practices in the palm industry related to draining of peatlands, deforestation, and the alleged killing of orangutans brought to light by NGOs, and the result is that other feedstocks have prevailed over the technical potential of palm.

These interactions are not always restricted to a singular feedstock. The debate over palm, and the extent to which claims of pro-biofuel industrial organizations and anti-biofuel NGOs may or may not be backed by evidence, has extended beyond this particular feedstock, causing many to dismiss biofuels as renewable altogether, largely as a result of this debate. Many anti-biofuel NGOs were created specifically to monitor negative effects of biofuels, in response to perceived environmental injustices. One such organization, the British NGO Biofuelswatch, cautioned that “biofuels should not automatically be classed as renewable energy” in an interview with the New York Times (*117*).

The extension of influence in stakeholder interactions is also likely to expand with increased use of social media which allows stakeholders direct access to information and each other. An example is an extension of the palm oil debate. In

2009, the NGO Greenpeace began a campaign targeting a single palm oil producer, Sinar Mas, which had relationships with many large companies including Nestle, Cargill, Burger King, General Mills, and Unilever. The company was identified by Friends of the Earth in 2006 in relation to the biofuels debate, and is a major producer of forest products and palm oil with activities in Indonesia (*45*). Greenpeace UK went after Nestle in a “bloody” campaign through traditional protests and on-line actions, the most notable of which was a graphic You-Tube video, released in March, 2010, depicting an office worker eating a trademark Kit-Kat chocolate bar which was represented as orangutan fingers complete with spurting blood (*118*). Salter Baxter illustrated the interaction of stakeholders involved in the campaign through websites, blogs, and other media related to the discussion (*119*). In the analysis, 70% of the conversations regarding palm oil occurred via blogs with 30% of the coverage being classified as negative. Companies responded in different ways. Nestle severed all ties with Sinar Mas, released responsible sourcing guidelines, and participated in a negative statement regarding use of oils for biofuel (*120*, *121*). Cargill maintained its relationship with Sinar Mas, entering into sustainable production discussions with the World Wildlife Foundation, and remained neutral but guarded regarding the biofuel issue (*122*). Burger King also severed ties to Sinar Mas but appeared to be the only company that went beyond their corporate website to social media engaging stakeholders through Facebook.

The ability to follow such stakeholder interactions via internet activities offers a new tool by which to understand stakeholder choices and the influences of stakeholders on each other. Additionally, the ability to easily and inexpensively engage stakeholders in interpersonal dialogue changes the classic one-way communication paradigm offered by conventional media and advertisement. Social media is not only almost instantaneous, it is largely unsupervised. This creates additional challenges to all stakeholders regarding the veracity of information. The exploitation of emotion over fact is not a new phenomenon but the rapidity with which emotional responses can be amplified by social media creates a new and very real problem for stakeholders suddenly forced to defend themselves against untrue claims and repair damaged relationships. Such efforts require time, energy, and money, and can delay progress or derail it entirely. The effects of these novel mechanisms for stakeholder interactions on choices regarding next-generation feedstocks are not yet clear.

Conclusions

Understanding the values of individual stakeholder groups is crucial to understanding how feedstocks will be selected. At present, concerns regarding environmental and economic sustainability dominate the interactions between biofuel stakeholders regarding feedstock choices. In particular, the use of food and feed crops for biofuels (first-generation biofuels) has become extremely controversial. As a result, the development of advanced biofuels such as cellulosic ethanol and low-carbon drop-in fuels is being incentivized. A number of interesting non-food biomass feedstocks have emerged that may enable production of low-carbon renewable fuels (next-generation biofuels) without substantial impacts on food and feed production and avoiding many of the negative long-term environmental impacts of some conventional agricultural practices. In this regard, scientists and researchers play crucial roles generating the knowledge required for decision-making and as honest brokers of information for stakeholders across the biofuel production and value chains.

The development of new feedstocks requires cooperation of growers and biofuel companies to pair technologies to regionally appropriate biomass. Feedstock producers (farmers and foresters) are key decision-makers in making these new fuels possible. Farmers face uncertain markets for biomass feedstocks because the biofuel facilities have not yet been built and biofuel producers and investors are unwilling to site projects without a stable supply of feedstock in place. Feedstock contracts have emerged as an important instrument to align values of feedstock producers, biofuel producers (biomass consumers), and investors. While technological advances may allow more fluidity in feedstock/product pairing in the future, this first spate of plants is aligning specific feedstocks well in advance of implementation. The vast majority of companies that are planning commercial-scale facilities by 2016 have already contracted their biomass supplies and many have begun programs to grow, harvest, and store biomass in advance of any construction efforts.

Policy makers, NGOs, researchers, and consumers exert additional influence on the primary stakeholders through a variety of interactions. Policy instruments, in particular, have been pivotal in moving development of next-generation biofuel feedstocks forward amid a climate of uncertainty, economic instability, and a risk-averse investment trend. While feedstocks can be rejected via any number of antagonistic interactions among these stakeholder groups, feedstock selection requires substantial alignment of stakeholder values. In fact, all of the commercial-scale cellulosic ethanol projects moving forward have leveraged synergistic interactions between multiple stakeholder groups to align feedstock availability with the production needs for individual facilities. Although these projects are developing a wide variety of lignocellulosic feedstocks, the majority are embracing residual or waste biomass with only a few pursuing dedicated energy crops. The evolving policy landscape, with changing definitions of renewable biomass, will continue to affect feedstock choices for some time to come.

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Chapter 4

Inventories and the Global Food-Commodity Prices

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Prices of major food commodities, such as corn, soybeans, rice, and wheat, increased by two to four fold between 2001 and 2007. A number of existing studies have identified several influences on these price increases, including increased food demand with economic growth, expansion of biofuels, food price increases due to exchange rate fluctuations, increases in energy prices, as well as speculation, trade policy and weather shocks. The study shows that commodity inventory demands also are an important influence, and that not accounting for this factor leads to misleading conclusions about other price influences. A simulation model shows that when the effects of inventory expansion *are* taken into account, the estimated overall impact on prices of economic growth, increased energy prices, biofuel expansion, and exchange rate fluctuations is roughly 12 percent smaller. This is a significant finding in light of the controversies surrounding various influences on food prices, and indicates that inventory management is an important policy measure to dampen food price increases.

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
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Keywords: Biofuels; Biomass; Economic Growth; Energy Prices; Exchange Rate; Food; Fuel

1. Introduction

Since the beginning of the current millennium, we have witnessed periods of rising food and fuel commodity prices that reached record levels by mid-2008 (*10*, *15*, *19*). These trends have reemerged during recent years. Although prices declined throughout most of 2009, world food prices rose to a record high in December 2010, because of higher sugar, grain, and oilseed prices exceeding the levels reached in 2008 (*10*). At the same time, we have witnessed growth in the production of biofuels. From 2001 to 2008, global ethanol production from maize and sugarcane more than doubled from 30 billion liters to 65 billion liters while biodiesel production from edible oil seeds, such as soybean, oil palm, and rapeseed, expanded sixfold from 2 billion liters to 12 billion liters (*14*).

The impact of the expansion of biofuels on food commodity prices is a subject of much controversy. While there is a large literature addressing this topic, most of the literature ignores the role of inventories and thus overestimates the impact of biofuels. Inventory adjustments slow the food commodity price inflation, but the inventories became depleted over time resulting in food commodity prices soaring during 2007-08 and, again, in 2010. By 2008, the stocks-to-use ratio declined to historical lows as did inventory levels. This was the outcome of successive years of consumption exceeding production, which can be traced all the way back to 1985 (*20*, *21*).

Covering the period 2001-2008 we show that food commodity prices spiked because the growth of demand for food and feed outpaced supply and, for most crops, the main contributor to the increase in demand was economic growth measured with gross domestic product (GDP) per capita. Biofuels affected the price of some crops more than others. The share of crops allocated to biofuels is substantial for rapeseed but not for corn and soybeans. This resulted in biofuel becoming an important factor for an increase in the price of rapeseed but less important for other crops. Whereas corn ethanol was responsible for about a 20% increase in the corn price in 2007 relative to 2001, soy biodiesel was responsible for about a 9% increase in soybean prices in 2007 relative to 2001.

Food-price inflation can be addressed in the longer run by expanding supply and investing in Research and Development (R&D) as well as investing in technologies that reduce the impact of factors on demand for staple crops (e.g., investing in second-generation biofuels)—for more on the cost of second generation biofuels, see references (*7*) and (*13*). Policy should create conditions that lead to the expansion of adoption of supply expanding technologies. In the short term, international agencies may develop food-security strategies that are based on inventory levels. Another possibility would be to have flexible policies, such as biofuel mandates that depend on food prices, thus making more food available for consumption during the periods of high prices.

We introduce the empirical multimarket model of inventory in section 2. Section 3 describes the results from the numerical simulation. This section demonstrates the importance of understanding the market for inventory to better predict the effect of any large supply or demand shock on food commodity prices. Section 4 concludes and discusses the policy implications from the analysis.

2. The Analytical Framework

Worldwide growth in demand during the last several decades, coupled with a slowdown in agricultural production growth, reduced global inventories of basic commodities, such as corn, soybeans, and wheat (*20*). A clear downward trend is observed for rice, wheat, maize, and rapeseeds but not for soybeans (Figure 1).

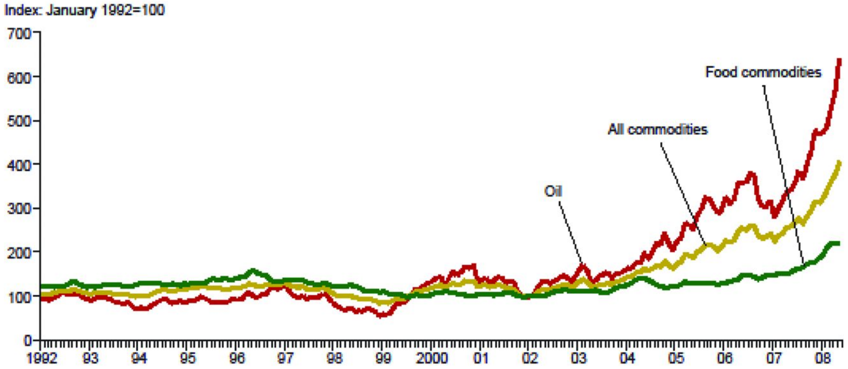

Figure 1. Commodity price trends (19).

The decline in inventories, coupled with the increase in global demand, resulted in a steady but gradual decline in stock to use, which declined by more than 50%. The stocks-to-use ratio of world grain and oilseed stocks declined from 35% in 1985 to less than 15% in 2005 (*20*). Lower stocks, in turn, made it more likely that new sources of demand (e.g., biofuels), or disruptions to supply (e.g., drought), would result in large price changes.

Below, we present the empirical multi-market model of inventory, which we use to quantify the various factors. While section 2.1 discusses the various parts of the multi-market framework, the parameters used to calibrate the model and the different scenarios simulated are described in sections 2.2 and 2.3, respectively.

2.1. The Various Parts of the Multi-Market Framework

Our analysis decomposes the demand for basic commodities, such as corn, rice, soybeans, and wheat, to three parts. The first is food and feed, which is affected by economic growth and fluctuations in the exchange rate. Strong global growth in average income, particularly in developing countries, increased food and feed demand. As per-capita incomes rose, consumers in developing countries not only increased per capita consumption of staple foods but also diversified their diets to include more meats, dairy products, and vegetable oils (*20*). This, in turn, amplified rising demand for grains and oilseeds used as feed.

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The second are biofuels, where use has been modest for several decades, but production rose rapidly in the United States beginning in 2003 and in the European Union (EU) starting in 2005. Biofuel feedstocks, such as corn, sugarcane, soybeans, and rapeseed, now have new uses beyond food and feed. The demand curve now expands, and this expansion is affected by biofuel mandates and subsidies. Biofuel, similar to economic growth, caused the demand to shift up and to the right.

The third source of demand is inventories, where levels have been declining since 1985. The introduction of inventories to our analysis suggests that global consumption does not need to equal production in equilibrium, but it should equal production minus the change in the level of global inventories. That is, the current change in inventories equals the difference between production and consumption. If in the current period consumption outpaced production, then the difference is negative and inventories decline. However, if the difference is positive, then production is larger than consumption and inventories increase in the current period.

Another factor that we consider is the increase in energy prices. To this end, the energy price impact on food commodity prices should be divided into two factors: the allocation of land to biofuel crops (which reduces food and feed availability and increases the aggregate demand for food commodities) and the increase in energy prices (which increases production costs and reduces the supply of food commodities). First-generation biofuels, which are derived primarily from corn and sugarcane, compete with food and feed, resulting in higher demand for agricultural commodities and thus in higher prices. The introduction of biofuels, however, also lowers fuel prices (*16*). Yet, the literature fails to recognize that lower fuel prices affect farm-level costs. Introducing energy markets, with all of their complexities, to our multi-market framework reduces the impact of biofuels on food commodity prices further.

While incorporating the three demand elements described above, together with the biofuels and energy prices that affect supply of commodities for food, we argue that growth in world production was more sluggish, on average, and consumption outpaced production for most periods/crops. Declining real-food commodity prices over the last several decades (see, for example, http://www.indexmundi.com/commodities/) reduced incentives for maintaining food stockpiles and for funding research and development to increase yields. Regulations in key regions also hampered research and development of yield-enhancing technologies (*1*). This, together with strong demand growth, depleted inventories and led us to the 2007-08 price spikes. Rice is an exception, and trade restrictions played a key role in the spikes in rice prices (*8*). Rice-exporting countries limited exports to mitigate upward pressure on domestic prices only to exacerbate the spike in the price of rice in the rice-importing countries (which includes many least-developing countries).

The numerical model used to quantify the effects discussed above was developed in reference (*12*). It assumes a multiregion framework, where demand for each crop is composed of food/feed; inventory; and, where applicable, demand for biofuels. The model is applied for five major crops: corn, rapeseed, rice, soybeans, and wheat. With the exception of rice and wheat, all the other crops are currently being used to produce biofuel.

Biofuel from corn, rapeseed, and soybeans is jointly produced along with a coproduct that is, itself, a substitute for the raw grain or the oilseed. For instance, in the case of corn, 1 bushel (56 pounds) of corn yields approximately 2.75 gallons of ethanol and 18 pounds of distiller grains, which is a substitute for corn grain. A fraction of the quantity of the original crop used for biofuel is replaced in the form of a coproduct. Therefore, for these three crops, we compute an effective demand of the particular crop for biofuel, which equals the crop consumption for biofuel minus the quantity of a coproduct. In the case of corn, the effective demand of corn is $0.68(= 1 - 18/56)$ bushels per 2.75 gallons of ethanol. We assume that biofuel production function is of the Leontief (fixed-proportion) type.

We divide the world into seven major regions, namely, Argentina, Brazil, China, EU (EU-27 countries), India, United States, and an aggregate that represents the rest of the world (ROW), and focus on the time period between the years 2001 and 2007.

There are two major approaches for modeling inventories for basic crops, such as corn, soybeans, wheat, and rice. References (*22*) and (*23*) emphasize arbitrage and speculation in generating demand for inventories, while reference (*4*) emphasizes the dynamic adjustments by producers. We assume that a demand for inventories exists and calibrate it. In particular, we assume that the crop demand for inventory is represented as a nonlinear function of price and follows reference (*5*) and (*6*). This model suggests that larger changes in inventory levels would correspond to smaller changes in crop prices.

2.2. Model Calibration

We calibrate the crop-supply and crop-demand functions for each crop, region, and year, once with demand for inventory and once without. The calibrated demand and supply parameters are used to numerically calculate the effect of each of the different shocks on the observed price in a given year.

Key parameters in the calibration of these functions are elasticities of supply and demand, i.e., the sensitivity of a relative change in quantities supplied or demanded to a given relative change in (energy) prices. Given the wide range of elasticities reported in the literature and the sensitivity of the simulation to elasticities, for each crop, we chose to sample 100 times from within a range of elasticities. The range of elasticities is shown in Table 1. The elasticity of supply and food and feed demand with respect to energy prices is assumed to lie within the range [-0.15,0] and [-0.05,-0.02], respectively. This reflects the assumption that food and feed demand is less responsive than is supply to energy prices.

Note that our specification does not include cross-price elasticities on the supply or the demand side. This limitation prevented us from quantifying the effect of competition for land, whose supply is inelastic. The reason for this is to overcome computational constraints. We chose to investigate the robustness of the results through a sensitivity analysis with respect to own-price, income, and energy elasticities and by employing alternative specifications of the demand function. Our computational capacity did not allow us to introduce cross-price elasticities to this numerical exercise. This limitation will be addressed in future work.

Following references (*5*) and (*6*), we estimated the inventory demand parameters using instrumental variable techniques. Because inventory is correlated with the disturbance, whereas harvest is uncorrelated with these disturbances but correlated with inventory (harvest is both exogenous and relevant), we estimated the inventory demand function while using harvest as an instrumental variable. We tested alternative specifications and also introduced crop-specific dummy variables. In all cases, however, we could not reject the hypothesis that the specification chosen is correct.

Given the relevant elasticities for each region, we calibrate the various parameters (the data sources are listed in the Appendix). As one can see, the shocks eliminate changes in income, biofuel mandate, exchange rates, and energy price between 2001 and a specific year during 2002 to 2007. These shocks reduce prices and are presented in the figures throughout the text. Our analysis also generates tables that present the inverse outcomes, namely, what are the rates of increase in prices because the changes that occurred.

Table 1. Range of elasticities contained in the literature (available at http://www.ers.usda.gov/Data/Elasticities/ and http://www.ers.usda.gov/Data/Elasticities/)

		Supply (a)		***Demand*** (b)		***Income*** (c)	
Commodity	***Region***	***min***	***max***	***min***	***max***	***min***	***max***
Corn	**Argentina**	0.65	0.75	-0.4	-0.3	0.35	0.45
	Brazil	0.37	0.47	-0.4	-0.1	0.35	0.45
	China	0.08	0.18	-0.14	-0.6	0.75	1
	EU	0.01	0.13	-0.44	-0.24	0.1	0.2
	India	0.16	0.26	-0.28	-0.22	0.75	1
	U.S.	0.45	0.55	-0.24	-0.1	0.05	0.1
	ROW	0.45	0.55	-0.43	-0.21	0.4	0.6
Soybeans	**Argentina**	0.27	0.37	-0.3	-0.2	0.35	0.45
	Brazil	0.29	0.39	-0.21	-0.11	0.35	0.45
	China	0.4	0.5	-0.25	-0.15	0.75	1
	EU	0.14	0.24	-0.3	-0.2	0.1	0.2
	India	0.31	0.41	-0.35	-0.25	0.75	1
	U.S.	0.18	0.28	-0.48	-0.31	0.05	0.1
	ROW	0.18	0.28	-0.48	-0.31	0.4	0.6

Continued on next page.

Table 1. (Continued). Range of elasticities contained in the literature (available at http://www.ers.usda.gov/Data/Elasticities/ and http://www.ers.usda.gov/Data/Elasticities/)

		Supply [(a)]		*Demand* [(b)]		*Income* [(c)]	
Commodity	***Region***	***min***	***max***	***min***	***max***	***min***	***max***
Rapeseed	**Argentina**	0.53	0.63	-0.35	-0.03	0.35	0.45
	Brazil	0.53	0.63	-0.35	-0.03	0.35	0.45
	China	0.21	0.31	-0.35	-0.25	0.75	1
	EU	0.23	0.33	-0.13	-0.03	0.1	0.2
	India	0.29	0.39	-0.3	-0.2	0.75	1
	U.S.	0.53	0.63	-0.35	-0.03	0.05	0.1
	ROW	0.53	0.63	-0.35	-0.03	0.4	0.6
Rice	**Argentina**	0.27	0.37	-0.43	-0.38	0.35	0.45
	Brazil	0.27	0.37	-0.43	-0.38	0.35	0.45
	China	0.27	0.37	-0.71	-0.54	0.75	1
	EU	0.27	0.37	-0.43	-0.38	0.1	0.2
	India	0.27	0.37	-0.43	-0.38	0.75	1
	U.S.	0.27	0.37	-0.87	-0.77	0.05	0.1
	ROW	0.27	0.37	-0.43	-0.38	0.4	0.6
Wheat	**Argentina**	0.36	0.46	-0.39	-0.28	0.35	0.45
	Brazil	0.38	0.48	-0.38	-0.27	0.35	0.45
	China	0.04	0.14	-0.18	-0.07	0.75	1
	EU	0.07	0.17	-0.33	-0.26	0.1	0.2
	India	0.24	0.34	-0.37	-0.32	0.75	1
	U.S.	0.43	0.53	-0.35	-0.25	0.05	0.1
	ROW	0.43	0.53	-0.35	-0.25	0.4	0.6

(a) Own-price elasticity of supply. (b) Own-price elasticity of demand. (c) Income elasticity of supply.

2.3. Numerical Scenarios

Given the cumulative change in a variable with respect to the year 2002, we use the market-clearing condition to derive a counterfactual equilibrium world price for each crop for the various shocks for each year. We do so for three different alternative scenarios, which either differ in the assumed range for elasticities used in calibration of supply and demand functions, or differ in the specification of the demand for food/feed (whether GDP per capita is explicitly represented in demand), or differ in parameters of the inventory demand function. The motivation for considering these alternative scenarios is to determine the robustness of our results.

The first scenario, which we, henceforth, refer to as the *baseline scenario,* is one in which we use the range of elasticities reported in the literature, namely, that mentioned in the U.S. Department of Agriculture (USDA) database of elasticities and in the FAPRI database. Under this scenario, the parameters for the inventory demand function are those that we estimate ourselves using the specification of references (*5*) and (*6*). As mentioned earlier, we perform 100 simulations of this scenario for the various shocks for each crop and for each time period. In the second scenario, the *inelastic scenario*, we assume a narrower range for elasticities, which is, on average, more inelastic compared to the baseline scenario and follows reference (*11*). Finally, to test the robustness of the inventory demand parameters, we simulate a fifth scenario using references (*5*) and (*6*) estimates for the inventory demand function as opposed to our own. Note that references (*5*) and (*6*) estimate the inventory demand based on U.S. data for 2006 through 2008 while we use world data for 2001 through 2008.

3. Results

We report two different price changes, where $i \in$ [biofuel, economic growth, energy prices, exchange rate]:

1. Reduction in commodity price if key variables would have stayed at their 2001 levels, $\Delta P_{t,i}$.
2. The increase of the commodity price is attributed to a change in one of the variables between 2001 and the specific year, $\Delta P_{t/2001,i}$.

The simulations compute $\Delta P_{t,i}$. We then compute $\Delta P_{t/2001,i}$ as follows, where ΔP_t^a denotes the total percentage price change between the year t and year 2001:

$$\Delta P_{t/2001,i} = \Delta P_{t,i}\left(1+\Delta P_t^a\right)/\,\Delta P_t^a. \tag{1}$$

Total change in price from year t to year 2001 that is explained by our model equals the sum of $\Delta P_{t/2001,i}$ over all the shocks. The figures depict $\Delta P_{t,i}$ (namely, the food commodity price reduction attributed to a shock that eliminates one of the factors that caused prices to change after 2001) whereas the tables show $\Delta P_{t/2001,i}$ (namely, the increase in commodity prices from 2001 attributed to one of the factors that caused prices to change after 2001). In both cases we report the mean outcome of 100 simulations. When presenting prices for different crops, we distinguish between two different specifications: one with inventory demand function and another without inventory demand. For each crop, we show the impact of these shocks one at a time.

The observed prices for the different crops are shown in Figure 2. A clear upward trend, on average, emerges for all crops, albeit some prices increase more than others. Whereas the price of corn and soybeans increased from 2002 to 2006 by about 63%, the price of wheat increased by more than 74%. Furthermore, while some crops, such as rice and wheat, experienced an upward trend throughout the period, others, such as soybeans, declined in 2005 and 2006 only to increase by 39% in 2007.

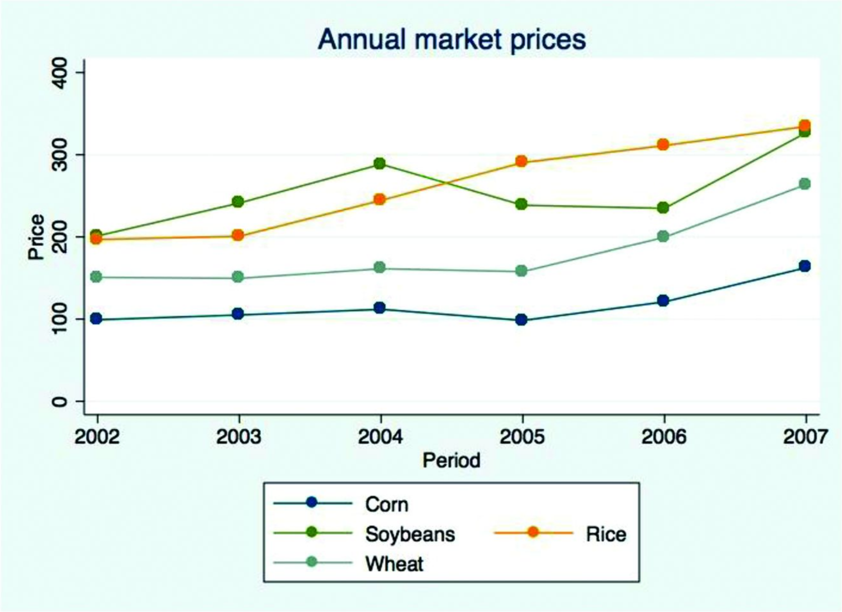

Figure 2. Average (actual) annual prices (in US 2005 $ per tonne).

Because rice and wheat are not utilized for biofuels in any significant quantities, and since rice and wheat do not generally compete with corn, sugarcane and oilseeds (*9*), we assumed that the prices of rice and wheat are not influenced by biofuels (in general, biofuels may affect the supply of wheat because wheat and corn may compete for land—however, because of computational complexity we do not include these effects and assume no cross-price elasticities on the supply side). Furthermore, while a significant factor contributing to the food commodity inflation, biofuels are neither necessary nor sufficient for the food commodity price spike that we observe for 2007-08.

Inventory theory predicts that prices decline when inventory accumulates and vice versa. The data confirm these predictions, except for soybeans, and show similar trends for stocks-to-use ratio. Inventory affects prices, and serves as a buffer, as long as inventory levels are sufficiently large. However, as these levels become small, prices become more volatile and sensitive to the numerous specific factors affecting crop prices. We observe this relation, and less fluctuation is observed if inventory demand is explicitly added to the analysis (Table 2). The aggregate demand curve becomes much more elastic for large inventory levels and, thus, predicts less price volatility.

Table 2. Contribution of various factors on increased price of selected food commodities (% price increase from counterfactual scenario in a given year)

	With inventory			*Without inventory*		
	Year			*Year*		
Crop	*2005*	*2006*	*2007*	*2005*	*2006*	*2007*
Biofuel shock						
Corn	4.4%	6.8%	9.8%	5.5%	7.4%	9.8%
Soybeans	1.0%	1.8%	3.4%	1.5%	2.6%	4.1%
Rice	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Wheat	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Income shock						
Corn	7.9%	12.2%	15.3%	12.4%	16.7%	19.5%
Soybeans	6.3%	8.9%	14.7%	12.1%	15.6%	22.1%
Rice	11.6%	13.5%	16.1%	20.9%	27.9%	35.1%
Wheat	11.1%	16.0%	21.2%	15.1%	21.4%	27.7%
Exchange-rate shock						
Corn	3.5%	5.0%	7.6%	4.6%	6.2%	9.4%
Soybeans	1.0%	2.4%	5.3%	1.4%	3.8%	7.9%
Rice	3.3%	4.0%	6.5%	6.7%	8.3%	14.4%
Wheat	6.6%	7.3%	11.0%	8.1%	8.9%	13.1%
Energy-price shock						
Corn	2.2%	2.9%	2.9%	3.3%	3.6%	3.6%
Soybeans	1.9%	2.4%	2.4%	3.6%	4.0%	4.0%
Rice	3.0%	3.0%	3.0%	2.4%	2.6%	2.6%
Wheat	2.8%	3.1%	3.1%	3.6%	4.0%	4.0%
Aggregate effect of all four shocks						
Corn	18%	27%	36%	26%	34%	42%
Soybeans	10%	15%	26%	19%	26%	38%
Rice	18%	20%	26%	30%	39%	52%
Wheat	20%	26%	35%	27%	34%	45%

The model explains the fluctuation in prices. It captures the effect of biofuel, economic growth, energy prices, and exchange rate on food commodity prices. The paper does not introduce population growth, speculation, trade policy, or factors such as productivity growth and weather shocks to the analysis. Next, we calculate how much of the total price change the simulation explains, correcting for yield effects reported in the literature (*2*). Supply shift, due to yield increase, reduced upward pressure exerted by the increase in demand. Thus, and building on reference (*2*), we use the slope of the supply function, and assume yield growth of 1.5% shifts supply to the right, and compute ΔP_{yield}, i.e., line segment GA in Figure 3. Then, the amount explained, $\Delta_{\lambda E}$, by our model is simply

$$\Delta_{\lambda E} = \frac{\Delta P_t}{\Delta P_t^a + \left|\Delta P_{yield}\right|}, \tag{2}$$

where $\Delta P_t = \sum_i \Delta P_{t,i}$ is the sum of the price change explained by the different shocks ($i \in$ {biofuel, economic growth, energy prices, exchange rate}). Recall that ΔP_t^a is the price change observed between period t and 2001, i.e., line segment HC in Figure 3. Table 3 shows the total explained price increase with respect to 2001.

The amount of the price fluctuation explained by our model is different for different crops, in part because the omitted factors affect some crops more than others. For instance, we did not add trade policy shocks, which affected rice, and we do not have weather shocks, which adversely affected wheat (see http://www.ers.usda.gov/AmberWaves/November07/Findings/Global.htm).

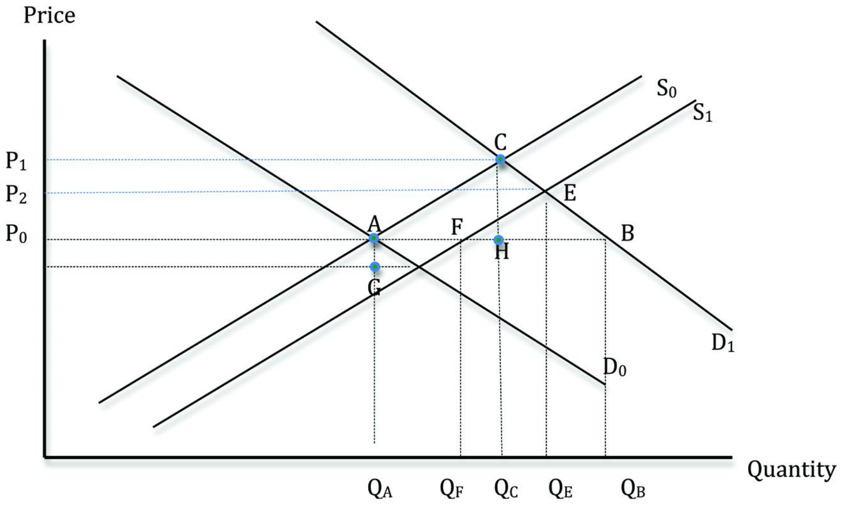

Figure 3. Total explained price change.

Table 3. Total percent price change in 2007 explained by numerical model

% explained	*with respect to 2001*
Corn	70%
Soybeans	55%

The study by Baffes and Haniotis (*3*) suggests that the role of demand is not as prominent because of the low level of growth in consumption during the investigated period, especially in the case of wheat and rice. However, changes in consumption are different than changes in demand. Growth in income, coupled with high-income elasticity, contributed to the increase in demand. Yet, production did not grow much, especially in the case of wheat and rice. So the growth in supply was modest, leading to a modest increase in consumption but a large increase in price. The rate of growth in consumption of soybeans and corn was higher than wheat and rice, reflecting larger productivity gains (*18*). But, as income grew, demand for meat and thus demand for feed grew as well, resulting in an increase in prices and reduction of inventories. Thus, economic growth is an important contributor to the rise in food commodity prices. The study by Baffes and Haniotis (*3*) also emphasizes the role of commodities by financial investors in 2007-08 food-commodity price spikes, which we did not investigate.

3.1. Robustness

Key parameters in our analysis and in simulation-based models, in general, are the elasticities, which are used to calibrate the demand and supply curves. The alternative specification, denoted the *inelastic scenario*, assumes lower elasticities. The elasticities used were obtained from well-known and widely used sources, such as the FAPRI elasticity database (available at www.fapri.iastate.edu/tools/elasticity.aspx) and the USDA elasticity database (available at http://www.ers.usda.gov/Data/InternationalFoodDemand/). However, according to several other researchers, the elasticities of supply and demand for agriculture are more inelastic than those reported in the above databases. For instance, see reference (*11*) for a discussion of supply and demand elasticities for agricultural commodities (Using world data on four major crops, namely, corn, soybeans, wheat, and rice from 1960 to 2007, Roberts and Schlenker (*17*) estimate that the short-term, own-price elasticity of supply and demand for calories from these crops is less than 0.15 and greater than -0.1, respectively). So that the elasticities would be, on average, lower than those in the baseline scenario and also conservative, we chose own-price supply elasticities in the range 0.2 to 0.3 and own-price demand elasticities in the range -0.3 to -0.2. Employing these elasticities, we find that the main qualitative conclusions regarding the importance of the different shocks from the baseline scenario, again, hold.

Other robustness checks included the baseline scenario with no income effect, an inelastic scenario with an income effect and price effect of shocks using inventory specification of references (*5*) and (*6*). All of the alternative specifications resulted in similar, although not identical, conclusions and suggested that biofuels, although an important factor, are not the culprit of the food commodity price inflation of 2007-08.

4. Conclusion

This paper focuses on four key factors responsible for the food commodity price inflation, namely, economic growth, biofuel expansion, exchange-rate fluctuations, and energy-price inflation on crop prices. The paper demonstrates the importance of incorporating inventory in analyzing the impact of biofuels and other factors on commodity food prices. The analysis suggests that, during periods of large inventories, the impact of shocks such as economic growth, are muted compared to no inventories and that this impact diminishes as inventory levels decline. Although inventory declined during the period of 2001 to 2008, inventories did serve as a buffer and reduced the impacts of shocks relative to no inventory. Thus, we find that the four key factors responsible for the food commodity price inflation of corn, soybeans, rapeseed, rice, and wheat caused prices to increase by 29% to 47% in 2007 and that these shocks were responsible for 49% to 71% of the increase in prices since 2001. However, a model without inventory demand predicts that prices increased by 49% to 63% in 2007 and that these shocks were responsible for 73% to 87% of the increase in prices since 2001. Abstracting away inventory leads to predictions with higher price volatility. Overall, we show that, for most crops, economic growth was the largest factor responsible for the price spike in food commodity prices. Biofuel was the major factor for rapeseed, an important factor for corn, and a moderately important factor for soybeans, suggesting that, as long as biofuels are not a large share of the demand, the effect of biofuels on crop prices will likely be moderate at best. Whereas corn ethanol was responsible for a 26.5% increase in the corn price in 2008 relative to 2001, soy biodiesel was responsible for an 11.2% increase in soybean prices in 2008 relative to 2001.

Recent trends lend further support to the claim that factors other than biofuels are crucial to understanding the drivers of food price inflation. According to Food and Agriculture Organization (FAO) estimates, the world sugar price index declined by 13% from 2006 to 2008 when ethanol production in Brazil increased by about 2 billion gallons, but increased by 66% from 2008 to 2010 when ethanol production further increased by only 450 million gallons [available at http://www.fao.org/worldfoodsituation/wfs-home/foodpricesindex/en and http://www.ethanolrfa.org/page/-/objects/pdf/outlook/RFAoutlook2010_fin.pdf?nocdr=1]. The expansion of corn ethanol has, however, been more or less steady during both these time periods, having increased by about 4.2 billion gallons from 2006 to 2008 and 3.5 million gallons from 2008 to 2010. But, the world cereal price index, which increased by 97% between 2006 and

2008, has declined by 23% between 2008 and 2010. The correlation between the world price index for oils and fats and the expansion in global biodiesel production is similar to that between world cereal prices and U.S. corn ethanol production. Thus, while grain- and oilseed-based biofuels have witnessed a smaller but comparable increase since 2008, the corresponding commodity-price indices have both declined. Complicating matters is the fact that the latter time period has also been associated with trends, such as slower global economic growth, with more adverse weather conditions in Russia, a large wheat-producing and exporting region as well as new restrictive trade policies, such as the wheat-export ban in Russia and the rice-export ban in India [see http://online.wsj.com/article/SB10001424052702303678704576439832019176212.html]. Interestingly, according to the FAO's Assistant Director General, the recent volatility in world food price is attributable to: "a) the growing importance as a cereal producer of the Black Sea region, where yields fluctuate greatly from one season to the next; b) the expected increase of extreme weather events linked to climate change; and c) the growing importance of noncommercial actors in commodities markets" [see http://www.fao.org/news/story/en/item/45178/icode/]. Biofuels are conspicuous by their absence in this recent assessment.

One limitation of this paper is that some (important) crop-specific factors, such as weather and productivity shocks (especially for wheat) and trade policies (especially for rice), are not considered. Another factor not considered in this paper is the role of speculation or speculative activity. We elected to abstract from these shocks due to data and/or model limitations. Another limitation is that we looked at each market separately rather than in an integrated manner. Cross-price elasticities were not considered, which may lead us to underestimate the impact of the different factors on prices.

Although our conclusions are robust to a broad range of assumptions about the price elasticity of supply and demand for crops and parameters of the inventory demand function, an important area of future work is the empirical estimation of these parameters. Identifying correctly the inventory demand curve is a challenge and is a key step to accurately measuring the factors causing the food inflation of 2007-08. In future work we plan to further investigate these relationships and to introduce cross-price elasticities.

From a policy standpoint, the food crisis emphasizes the importance of both a proactive inventory management policy and the need for mechanisms that either compensate the poor when prices rise to abnormally high levels or simply mitigate the spike in prices. Such mechanisms may include biofuel mandates that adjust automatically to the situation in food markets and inventory-management policies. An alternative strategy is to set up international institutions that allow poor countries the option of acquiring food at a subsidized level while employing the future markets and subsidizing transaction costs of poor countries engaging in these markets. In the long run, expanding agricultural supply through investment in research and development, introducing regulation that would allow more effective utilization of existing technologies, and investing in outreach and infrastructure that will improve the management of food supply distribution and enhance productivity can reduce the likelihood of a food price spike.

Acknowledgments

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Appendix: Sources of Data

The various data sources are shown in Table 4. Data on production, consumption, beginning and ending stocks, imports, and exports for each region are obtained from the USDA Production, Supply, and Distribution database. Data on crop prices within each region are obtained from the FAO database. A key set of parameters in simulation models is the elasticities of crop supply and crop demand. Our specification of supply and demand requires information on elasticities of supply and demand with respect to own-price elasticities of supply and demand with respect to energy price and the income elasticity of demand. The range of elasticities contained in FAPRI database and in the literature cited by the USDA database is shown in Table 1.

Table 4. Sources of data

Data	***Source***
Production, consumption, and stocks in each region	USDA's Production, Supply, and Distribution Data base [a]
Domestic price of grains, sugar, and oilseeds	FAO [b]
World energy price	International Monetary Fund Primary Commodity Prices [c]
Biofuel production and consumption	Renewable Fuels Association [d]
Exchange rates	U.S. Federal Reserve Statistical Database [e]
Price and income elasticities of supply and demand for crops	Food and Agricultural Policy Research Institute Elasticity Database and USDA elasticity database [f]

[a] http://www.fas.usda.gov/psdonline.
[b] http://faostat.fao.org/.
[c] http://www.imf.org/external/np/res/commod/index.asp.
[d] http://www.ethanolrfa.org/industry/statistics/#E.
[e] http://www.federalreserve.gov/releases/G5A/.
[f] http://www.fapri.iastate.edu/tools/outlook.aspx.

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Chapter 5

Avoiding the Unintended Consequences of Bioenergy

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Increased bioenergy production can diversify energy portfolios, introduce renewable energy options, and help reduce the carbon footprint of the energy industry. Large-scale bioenergy implementation also has the potential to have negative environmental consequences as well. It is critically important to understand and minimize the potential unintended consequences of a transition to bioenergy. Biofuel development is complex and involves a variety of stakeholders with differing objectives. This makes reaching a consensus difficult. Biofuels are an emerging industry with some uncertainty as to how they will ultimately develop. The environmental profile of bioenergy development is unclear, with significant tradeoffs and conflicting evidence regarding the purported environmental benefits of bioenergy. Increased bioenergy production also has the potential to impact nitrogen, phosphorus, and water cycles. Carbon emissions also need further investigation, especially with respect to changing land use. This chapter will discuss the inherent tradeoffs between carbon, nitrogen, phosphorus, and land use that exist with bioenergy, and discuss preferable bioenergy development scenarios.

Bioenergy Development as a Wicked Problem

"Bioenergy" is a generic term for energy obtained from biomass. It pertains to the industrial development of alternative energy as replacements for traditional fossil fuel uses – primarily transportation fuels and electricity

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

generation. Biomass sources are highly varied and can be derived from numerous sources. Potential feedstocks include currently grown agricultural commodities such as corn or soybeans, biomass repurposed from alternate markets such as forestry products, waste products generated through animal feeding operations or municipal sources, and biomass not currently grown for commercial use such as perennial grasses (switchgrass, miscanthus), new agricultural products (genetically modified sorghum, jatropha), and industrially produced algal or bacterial biomass. In addition to a variety of potential sources, there are several ultimate uses of biomass for energy production. Although liquid transportation fuels in the form of ethanol or biodiesel dominate current markets, there is potential to transform biomass into higher value products such as jet fuel, gasify it into hydrogen or other products, or burn it for electricity generation. Generic discussion of bioenergy is therefore difficult due to the variety of feedstocks and potential end uses.

Development of bioenergy is a complex issue, involving many stakeholders and impacting economic, socio-political, and environmental issues. The complexity of bioenergy development and the difficulty involved in assessing its consequences, is best understood by comparing it to earlier environmental issues. For example, the burning of the Cuyahoga River, a landmark event in environmental management history, is ultimately a tame problem. In contrast, the environmental impacts of bioenergy development create a more complex problem to analyze, specifically because the problem is less obvious and not all stakeholders agree on the nature of the problems. This falls into a class of problems that have been designated as “wicked” (*1*). Ultimately, a problem is considered wicked if it does not have a simple problem definition nor a readily definable solution.

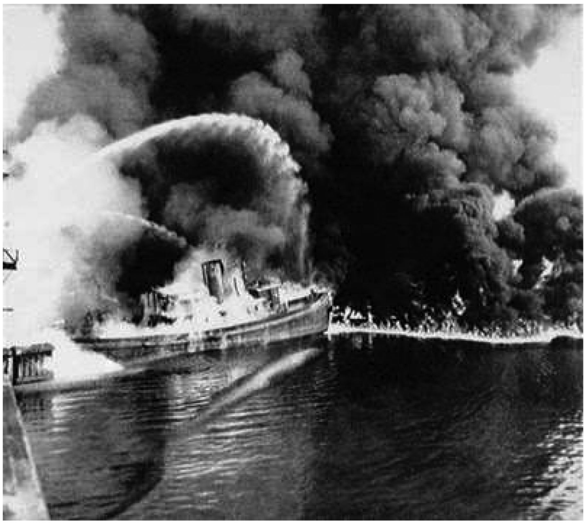

Figure 1. The Cuyahoga River Fire (2).

A Burning River as a Simple Problem

In 1969, the highly polluted Cuyahoga River famously caught fire and ignited major changes in environmental legislation. Interestingly, the 1969 fire was only one of thirteen times the river caught fire, and there is no known photograph of the 1969 incident. The photograph that was published in *Time* magazine and displayed in Figure 1, is a picture from a 1952 fire, which caused significantly more damage (*3*). The publicity surrounding the fire led to widespread public interest and outcry, summoning major changes in environmental legislation, contributing to the events that led to the passage of the Clean Water Act and the creation of the Environmental Protection Agency. Any number of environmental disasters could have had similar effects, largely because the problem itself was reasonably simple and it occurred at a time when public and political sentiment was attuned to environmental issues. In this way, the Cuyahoga River fire can be considered a tame problem in the terminology set forth by Rittel and Webber (*1*). It can be argued that the Cuyahoga River fire and resulting actions were able to occur due to its tameness. Specifically:

1) **Everyone agreed that there was a problem.** The river was on fire, and it was perceived as a problem. The problem was concrete, visually apparent, and understood by the public at large. It was neither abstract nor was it a problem that was a future possibility. Having an easily defined problem posing an obvious and immediate hazard was essential to resolving the issue. This is in contrast to some current environmental issues such as climate change or the environmental impacts of bioenergy production. While there is general consensus about the science surrounding these issues, they tend to be more contentious than earlier environmental problems. Bioenergy has numerous environmental consequences, but also poses potential environmental benefits such as being a renewable substitute for fossil fuels.
2) **Everyone agreed why it was a problem.** There was a growing public sense of morality surrounding environmental issues, and a river that was polluted enough to be flammable seemed wrong. Risks to property and human safety were also factors. Although this notion seems patently obvious, the twelve previous fires on the Cuyahoga did not motivate action. Until the 1960s when the environmental movement began to gain traction, industrial fires were largely seen as an unfortunate side effect of progress (*4*).
3) **Everyone agreed on the cause of the problem.** Pollution in the river created conditions conducive to fire. The underlying cause of the problem was virtually indisputable. Because there was little scientific uncertainty that the oil and debris floating at the river's surface were flammable, the fundamental cause was not open to debate. In contrast, modern environmental issues may not have a concrete causal link. This is particularly true with indirect land use change resulting from increased bioenergy production.
4) **Everyone agreed on the basic solution.** With a well-established cause-and-effect relationship, it was clear that reducing the level of pollution

would lessen the risk of fire. There were no other feasible alternatives other than cleaning up the river if the goal was to reduce the risk of future fires.

The resulting legislation and the process of river clean up was by no means easy; however, consensus on each of these four issues was able to expedite action. Many early environmental problems were similarly tame – not necessarily easy to fix, but fundamentally simple in construct. In most of these early cases, environmental damage directly resulted in some risk to health and human safety. The public had visceral reactions to issues that they understood and felt strongly about, as evidenced by similar outcry following other environmental disasters such as Love Canal, Bhopal, and Three Mile Island. In each of these cases, the problem was easily identified and agreed upon, the cause-and-effect relationship was apparent, and the basic resolution to the problem was straightforward.

Bioenergy Development as a Wicked Problem

In contrast to earlier examples of environmental disasters, current environmental issues are much more difficult to tackle. There may be disagreement on whether a problem exists, why it is a problem, the underlying causes, and how to resolve the issue. Especially when the issue is complex and the public does not readily understand the issue, it is also harder to reach consensus regarding what should to be done. Various modern environmental issues have been classified as "wicked", including climate change and the oil spill in the Gulf of Mexico (*5*, *6*). Bioenergy development conforms to the definition of a wicked problem, specifically because:

- There is not a solid consensus whether or the environmental benefits of bioenergy outweigh the environmental consequences. The problem definition relies on the stakeholder. Stakeholders with the objective to maximize rural economic development, for example, may believe bioenergy is extremely beneficial. The carbon footprint of a biofuel may be positive or negative depending on the inclusion of indirect land use change in an analysis. A problem for one stakeholder may be inconsequential, or even seen as beneficial, to another stakeholder
- The data needed to conduct analyses and inform decision-making contain large degrees of uncertainty or are not available. In fact, certain data may be impossible to obtain. This is particularly true for the case of indirect land use. There is no way to determine specific reasons a landowner began to grow crops or why agriculture expanded within a region. At best, indirect measurements of the phenomenon can be derived from commodity prices and mental models. But ultimately, the issue of indirect land use – and which land use changes are attributable to biofuels – will be based largely on theory rather than direct evidence.
- One of the key components of a wicked problem is that there is no way to tell when the problem is resolved. This is often called the "no stopping rule". Unlike the Cuyahoga River example, where success

> can be measured in river water quality and reduced risk of future fires, there is no true stopping point with bioenergy development. It is not possible to determine "absolute" success. Although a variety of goals and benchmarks can be reached, these goals are heavily reliant on the stakeholder(s) that determines the benchmarks and goals.

A wicked problem is inherently impossible to solve; therefore, the challenge is to better understand the landscape of decisions made with respect to bioenergy and minimize the risk of large scale unintended consequences. The analysis in this chapter is limited to environmental impacts of bioenergy, with particular focus on the non-carbon issues of biofuels. Economic and socio-political consequences may also be significant, and are treated elsewhere.

Environmental Consequences of Bioenergy

Although the environmental impact of every bioenergy product is different depending on the feedstock and end use, it is possible to make some generalizations about the environmental impacts of bioenergy. There are two major consequences associated with biofuels: changes in elemental cycles (C,N,P), and consumption of limited resources (land use, water use, potential displacement of fossil fuel resources). These consequences may be beneficial or negative depending on the way in which the bioenergy system is developed. In general, development of bioenergy reduces fossil fuel use and carbon emissions (*7*, *8*). Increased nitrogen and phosphorus runoff, and water and land use issues tend to be negative consequences of bioenergy development (*9*).

The issue that has received the greatest amount of attention in both academic circles and the popular press is carbon emissions and net energy balances. Initial concerns as to whether biofuels displace more energy than they consume during processing led to much discussion regarding net energy balances. Numerous life cycle analyses were performed on biofuels, with particular emphasis on corn ethanol. Although some conflicting results were obtained due to different boundary definitions and data sources in early studies, consensus suggests that direct life cycle carbon emissions from ethanol are fewer than those of gasoline (*7*). Carbon emissions resulting from indirect land use – land repurposed for food due to diversion of bioenergy – are less clear (*10*).

The concept of indirect land use change altered consensus regarding the potential carbon benefits of biofuels. When biofuels are produced on lands historically used to grow food, the supply of food from that land is removed. In theory, the food agriculture is displaced to another region of the world. Agricultural activities must either be intensified by increased use of fertilizer and chemicals or extensified by cultivating lands not historically used for crop production. When extensification occurs, the land use change to agriculture releases carbon from the soils and reduction in aboveground biomass, creating indirect carbon emissions (*11*). Indirect land use change and the subsequent carbon emissions is impossible to quantify directly, which makes the uncertainty surrounding these calculations significant. The true carbon benefits of biofuels

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are therefore unclear, and the large uncertainty ranges limit the amount that can be understood about the carbon footprint of biofuels (*12*).

Unintended Consequences: Non-Carbon Impacts of Biofuels

The majority of environmental impact studies of biofuels focus on carbon emissions. Even though the results of indirect carbon emissions are unclear, it is generally accepted that biofuels have fewer GHG emissions than fossil fuels when indirect land use change is not included. However, there are inherent tradeoffs between potential carbon benefits and non-carbon impacts. Biofuels have greater emissions of nitrogen and phosphorus, primarily during the agriculture stage as fertilizer runoff or volatile emissions (*8*). The non-carbon aspects of biofuels are equally important and often do not compare favorably to fossil fuels.

Nitrogen

Human activities have disrupted the nitrogen cycle to a greater extent than the carbon cycle, largely due to agricultural production (*13*). The size of disruption is due in part to the relative abundance of the elements and also to the various chemical forms that nitrogen can take. Nitrogen is found most abundantly in the atmosphere in a non-reactive state. Natural processes such as lightning or biological nitrogen fixation by selct plants can convert non-reactive nitrogen to a reactive state. Once in its reactive state, nitrogen can form amino acids which are essential for both plant and animal life. Prior to the manufacture of synthetic fertilizers, agricultural production was limited by nitrogen obtained from natural sources. In 1913, the Haber-Bosch process was demonstrated at an industrial scale, allowing conversion of atmospheric nitrogen to ammonia. By providing a synthetic source of nitrogen fertilizer, agricultural yields could drastically increase (*14*). Common agricultural practices is to maximize yields through fertilization, drastically increasing agricultural production.

Addition of synthetic nitrogen inputs altered natural elemental cycles. Areas that were once nitrogen-limited began to emit nitrogen in excess. This nitrogen could take on a variety of forms, including volatile emissions of ammonia, nitrogen oxides and nitrous oxide, and aquatic emissions of nitrate, and could cycle to different forms (*15*). Because these compounds exceeded natural assimilative capacities, these emissions contribute to a variety of environmental impacts including human health (NH_4^+, NO_3^-) , eutrophication (NO_3^-), smog and acid rain formation (NO_x), and climate change (N_2O).

Phosphorus

Phosphorus is also necessary for plant growth and development. Limited phosphorus supplies constrained agricultural expansion prior to the agricultural revolution when production of mined phophates became available. Phosphorus does not exist in volatile forms, so the majority of phosphorus impacts are aquatic. In phosphorus-limited aquatic systems, excess phosphorus can cause eutrophic conditions. Since most freshwater systems are phosphorus-limited rather than nitrogen-limited, excess phosphorus is responsible for the majority of eutrophic lakes, whereas nitrogen is primarily responsible for coastal hypoxia (*16*, *17*).

Unlike nitrogen which is highly abundant and easily cycled, phosphorus is in limited supply. The phosphorus cycle has only aqueous and solid phases and is primarily complexed as organophosphates or inorganic phosphate in a variety of forms (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4). With the exception of compounds such as potassium, sodium, and ammonium, most phosphate salts are insoluble and precipitate in water bodies. Phosphate is commonly found in geologic deposits and phosphate fertilizer is made by mining these deposits. Only minerals with high phosphorus contents, such as phosphorite, are commercially viable for agricultural fertilizer (*18*).

Because phosphates are non-volatile and often insoluble, the phosphate that was mined from concentrated mineral sources becomes dispersed throughout the environment once it is applied as fertilizer. Diffusion of phosphate becomes a problem not only due to non-point source pollution, but also from a supply chain management perspective since commercially viable sources of concentrated phosphate are finite. It is estimated that peak production of phosphorus mining could occur in as little as 30 years, and phosphorus supplies may be depleted within 200-300 years (*19*). Should bioenergy production become large enough to drastically change agricultural demands for fertilizer, the limitations of this resource could become even more problematic.

Water Use

Bioenergy can potentially impact water use and changes in regional water cycles. Increased irrigation may occur with an increase in bioenergy production (*20*), especially when crops can be profitable on lands that were once considered marginal. Agricultural regions such as the Southeastern United States which have historically not used irrigation practices due to cost considerations and the marginal nature of soils, may begin to irrigate crops if the economics are favorable to invest in irrigation infrastructure. Intensified irrigation has potential to stress groundwater resources (*21*). Finally, changes to regional water cycles may occur as a result of changing land use patterns, which may impact transpiration rates and hydrology of an area (*22*). These changes will vary considerably from region to region and are difficult to estimate.

Water is also necessary to process biofuels such as ethanol. Ethanol production requires between 3-4 gallons of water for every gallon of ethanol produced (*23*). This is reasonably modest for industrial use, with fossil fuel production requiring 2-2.5 gallons of water per gallon of gasoline (*23*). Irrigated corn requires 785 gallons of water per gallon of ethanol produced, representing a much higher burden, although most ethanol is manufactured from non-irrigated corn (*23*). The major concern is the location of the supplied water rather than the quantity. Addition of even small industrial demand in may stress select regions of the country. Most corn ethanol is produced in regions of the United States that are not water stressed. Cellulosic crops such as switchgrass and miscanthus are praised because they are drought-tolerant and can grow in water-stressed regions, particularly in areas of the Southwest which may not have been able to support agriculture in the past (*24*). Although the crops themselves may not impose additional water stress in the region, the processing into cellulosic ethanol may.

Finally, water is also an important consideration in the development of algal biofuels, which are expected to have promise as a future bio-oil sourse. Algae require water in which to grow. This is not problematic in closed systems where the water can be recycled. Open systems, however, have the potential for significant evaporative losses (*25*). This is particularly important in arid areas of the country with high solar inputs where there is high algal production potential, such as Arizona and Texas.

Land Use

Land use is one of the largest issues surrounding biofuels, yet one of the most difficult to assess (*26*, *27*). Converting from one land use into another has complex environmental, economic, and social consequences. A readily identifiable metric is difficult, and tends to be subjective to value one land use over another. Even neglecting socio-economic considerations, assessment of the environmental impacts of land use change is difficult because no single metric can adequately capture the impacts of land quality.

Most vegetative matter is significantly less energy dense than fossil fuels, with a metric ton of dry cellulosic material containing approximately 17-19 MJ/kg. Plant oils used for biodiesel production are significantly higher (25-40 MJ/kg) (*28*). For comparison, coal contains approximately 25 MJ/kg and crude oil is ~45 MJ/kg (*29*). In addition to the logistics of transporting this low density biomass and processing it into higher value fuel, the amount of land necessary to produce reasonably small quanties of energy are quite large.

In addition, land surface is limited and with the exception of algae which can be grown vertically in certain system designs, biomass grows horizontally, limiting the amoung of biomass that can be grown on a unit of land. Because of this limitation, bioenergy will never be sufficient to meet the world's energy demands (*30*). Since most productive lands are currently occupied by agriculture producing food, or ecosystems that need protection, the fraction of land available for bioenergy production is limited.

Two major factors are essential to understanding land use and biofuels: the quantity of area occupied and the environmental impact of that occupation (*31*). Area occupied is of direct relevance since land area is a limited resource and bioenergy production is limited by the amount o land available for energy production.

The environmental impact of land occupation can be more difficult to quantify due to the subjectivity of land quality. Objective measurements can be obtained to inform such an analysis. Changes in soil chemistry and gaseous emissions is one way to monitor environmental impact (*32*). For example, lands that are newly plowed for biofuel cultivation may emit carbon dioxide when they are disrupted. In other cases, perennial grasses may sequester carbon in soils. Biodiversity indicators are also common metrics that can be used. Biodiversity metrics do exist, such as counting the number of vascular plant species, but

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

are often unsatisfactory since it is difficult to estimate in absence of direct field measurements (*31*).

There are two categories of land use change: direct and indirect. Converting large tracts of land for energy production has direct impacts at the site of the land use change, as well as indirect impacts stemming from changes to global agricultural markets.

Direct Land Use

Direct land use is simply the area of land biofuel feedstocks occupy. Because new feedstocks such as switchgrass are currently not grown at production scale, large-scale promotion of switchgrass will require shifts in agricultural production. The types of land cover they displace will ultimately affect their direct environmental impact. Converting from a high intensity agricultural commodity to a perennial grass may accrue some net environmental benefits with respect to nutrient runoff and carbon sequestration in soils (*33*). Conversely, converting from a low intensity system where farming does not take place, such as in the Conservation Reserve Program (CRP) to farming a monoculture may have a negative effect (*10*).

Tilman et al have suggested that perennial polycultures have potential as bioenergy feedstocks that can be both high-yielding and environmentally beneficial (*34*). In this study, a mixture of native grasses generated higher yields than monocultures, promoting biodiversity, soil retention, and carbon sequestration. These results apply to unfertilized systems; however, unless a farmer is compensated for ecosystem services, the farmer will try to maximize profits by optimizing yields by applying fertilizer so nitrogen isn't limiting. Polycultural systems do not respond well to fertilization since lack of limiting resources allows a small number of species to become dominant.

Indirect Land Use

Indirect land use occurs when the cultivation of bioenergy displaces a previous crop to a different region. Often, the indirect land use occurs in a developing country (*11*). Largely because agricultural production in many parts of the world is not optimized, agricultural intensification often occurs. The quantity of lands indirectly cultivated due to the bioenergy cultivation cannot be directly determined, but are assumed to be less than 1:1.

Particularly with respect to carbon emissions, this is an issue since indirect carbon emissions have the potential to erase the carbon savings that result from switching from fossil to bio-based energy. Various researchers have proposed methods to capture this effect and the Low Carbon Fuel Standard was revised to include indirect carbon emissions in life cycle inventories of biofuels (*35*). Currently, the life cycle assessment process does not do a particularly effective job measuring the environmental impacts of direct land use change, it is difficult to determine how indirect land use change will ultimately be measured.

Selecting Preferred Biofuels

Biofuels can have very different environmental profiles, depending on the initial biomass source and the ultimate endproduct. Ethanol produced from sugarcane has very different life cycle impacts than ethanol produced from corn. Both products are quite different from forestry products that have been compressed into briquettes and are burned in power plants to produce electricity. When attempting to avoid the unintended consequences of bioenergy, it is important to evaluate not only a biofuel's impact relative to fossil energy, but also the relative impacts of a variety of bio-based products. Given that bioenergy production is already a growing industry, the appropriate question moves away from whether biofuels are preferable to fossil fuels and becomes a question of determining how to develop the industry with the lowest environmental impact and unintended consequences. It is important to determine the most effective use of land to produce biofuels and the most effective biofuels that can be produced.

Tradeoffs in Elemental Cycles

Prior life cycle studies have generally focused on the carbon aspects of biofuels and the degree of carbon savings that can be obtained when converting from a fossil fuel. By augmenting these studies with estimates of nitrate runoff, Figure 2 can be obtained.

Figure 2 shows the extent of tradeoff between carbon and nitrogen emissions, as well as providing some insight on which biofuels are preferred from a carbon and nitrogen point of view. Figure 2 shows nitrogen emissions on the x-axis. The y-axis shows the relative amount of greenhouse gas emissions as compared to a fossil fuel counterpart. In other words, the y-axis shows the relative amount of GHG emissions of biofuel when compared to the appropriate fossil fuel replacement. For ethanol and biodiesel, the biofuels are compared to gasoline and diesel. For electricity production, the comparison is to coal. Any positive value has net positive carbon emissions throughout its life cycle. A 0% represents a biofuel that is truly carbon neutral and has a net uptake of emissions. Values greater than 100% on the y-axis represent biofuels with more carbon emissions than fossil fuels. None of the bioenergy options presented here are carbon neutral. All have positive life cycle GHG emissions, although most exhibit improvements relative to fossil fuels. There are certain scenarios that could make corn ethanol emit more carbon emissions than gasoline; however, the majority of corn ethanol indicates carbon benefits.

It should be noted that carbon emissions resulting from land use change (both direct and indirect) is excluded from this analysis. In addition, both corn ethanol and soybean biodiesel produce co-products of distillers dry grains (DDGs) and soybean meal respectively, and allocation of the emissions to these co-products is included. Biofuels closer to the origin have lower carbon and nitrogen impacts than those in the upper right corner.

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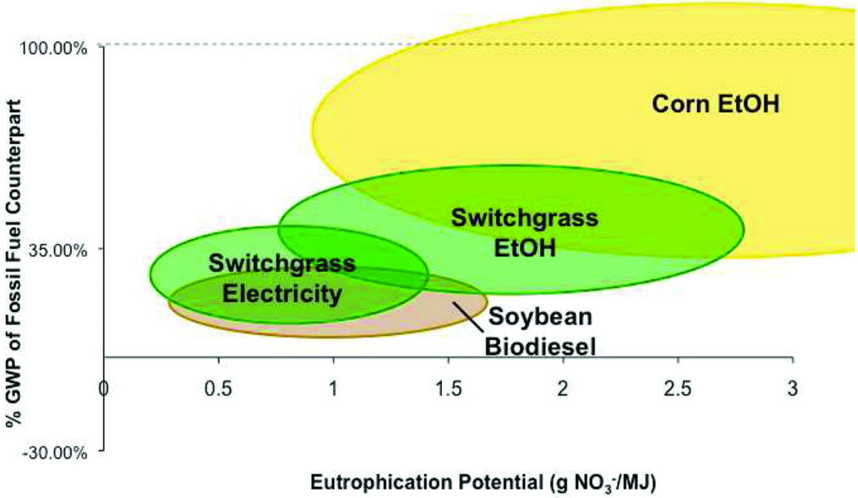

Figure 2. Carbon and Nitrogen Tradeoffs of a Variety of Biofuels. Adapted from Miller et al. (8).

Variability information is included using Monte Carlo Analysis (*36*, *37*). While the distributions incorporate both uncertainty and variability, it is variability that tends to dominate life cycle results. This is particularly true for biofuels due to the natural variability associated with agriculture (*37*) . Yields vary from year to year depending on temperature, precipitation patterns, and other natural variables. New technologies tend to perform better than older technologies (dry vs. wet milling, for example).

The data in Figure 2 demonstrates the large variability ranges. It is unreasonable to expect LCA studies regarding bioenergy to converge on a single value when measuring carbon and nitrogen emissions due to the inherent system variations associated with natural systems. In addition, certain bionergy technologies such as celluslosic ethanol, gasification, and algal biomass have not yet demonstrated commerial viability. Uncertainty in how these systems will develop leads to uncertainty in LCA results. Although the general trend indicates that switchgrass ethanol is preferable to corn ethanol from both a carbon and nitrogen perspective, this is not always the case. In certain circumstances, corn ethanol may be better than ethanol derived from switchgrass depending on the yields of the two crops, agricultural management practices, and ethanol processing efficiencies. And while it has been stated that electricity production is a more effective use of biomass than conversion to liquid transportation fuels (*38*), there may be certain circumstances where that is not the case given the variability of the results.

It therefore becomes difficult to make definitive statements about the preferability of one biofuel over another. Some of this variability cannot be avoided, yet a theoretical approach to look at the thermodynamics of systems can be used to understand the optimum energetic output from a variety of biomass sources.

Nitrogen and Land Use

In addition to tradeoffs in elemental cycles, the tradeoff with land use must be considered. It is reasonable to expect that biofuels that require the smallest land area to grow are preferable to those that require large land areas. Figure 3 plots the minimum theoretical nitrogen requirement with the maximum theoretical energy yield for fifteen crops (*28*), indicating the tradeoffs between land quantity needed and the amount of nitrogen needed by a variety of feedstocks.

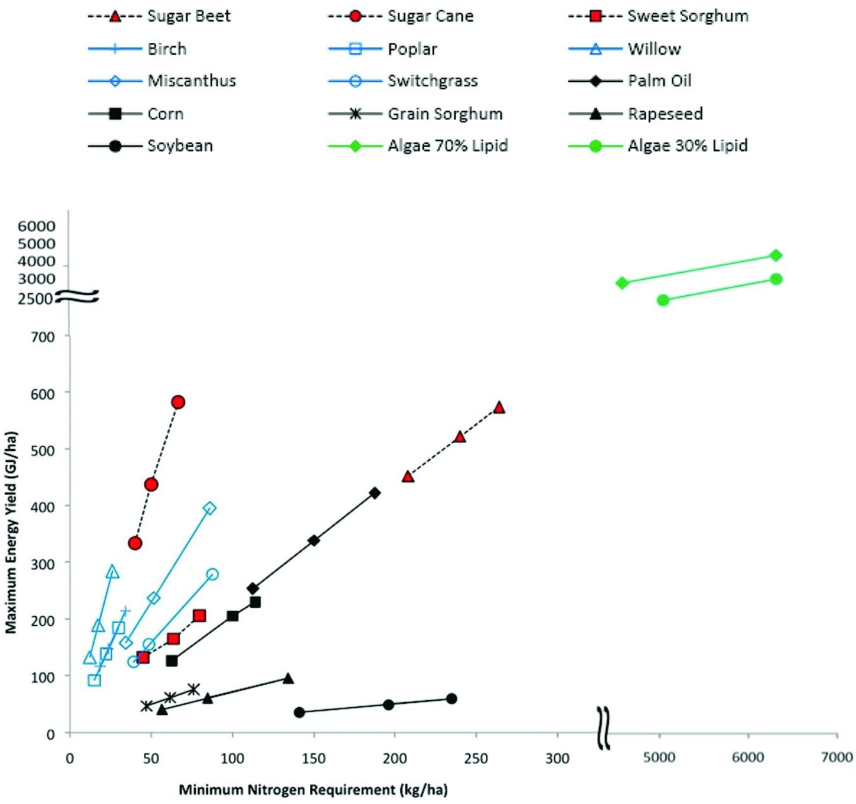

Figure 3. Land and Nitrogen Tradeoffs. Reproduced from ref (28).

The most desirable products have steep slopes and high energy yields. The crops are broken down into four basic categories: traditional food crops, cellulosic materials, sugar crops, and algae. As indicated in earlier work, the most effective crops for bioenergy are the sugar species due to high energy yields and low nutrient requirements (*28*). Cellulosic crops tend to be the next preferable, and current agricultural commodities produced for food purposes are the least desirable. Algae represents and interesting scenario with both biomass produced and nitrogen requirements orders of magnitude higher than the other feedstocks. If it is possible to manage nitrogen in algal systems effectively, algae has great promise as a high-yielding biofuel.

Summary

Bioenergy development has the potential to impact the agricultural system in a variety of ways. Interactions are complex and data can be difficult to obtain. The environmental issues associated with bioenergy are not always clear, making "sustainable" bioenergy development a much more complicated proposition than many earlier environmental problems. It is difficult to determine whether bioenergy constitutes an environmental improvement over fossil fuels given the tradeoffs in nutrients, water, and land use. Progress made on earlier environmental problems could be observed by measurable improvements in water and air quality. Improvements in the environmental profile of the bioenergy industry are complicated by the complex nature of land use issues and indirect supply chain effects, and a disconnect between the product and the life cycle stage where most of the impacts occur.

In light of this wickedness, special efforts are needed to avoid potential unintended consequences in bioenergy development. Choosing feedstocks that will minimize disruptions to elemental cycles and reduce demand for water and land resources are preferential to more intensive crops. Tradeoffs will always exist in complex problems such as bioenergy, but comprehensive analysis may help mitigate potential negative consequences.

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Chapter 6

Sustainability of Bioenergy from Forestry

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Modern forestry practices in the U.S. have developed around a set of sustainability concepts, practices and principles that can help inform the broader discussion around bioenergy. New concepts such as greenhouse gas emission profile are being included in proposed sustainability criteria for broader bioenergy feedstock production.

Introduction

Modern forestry practices in the U.S. have developed around a set of sustainability concepts, practices and principles that can help inform the broader discussion around bioenergy. In fact, the systems that have developed for forestry can be considered a model system for assuring sustainability in new bioenergy plantations and land use systems. This paper discussed how sustainability factors are woven into modern forestry practices, and the new concepts in proposed sustainability criteria for broader bioenergy feedstock production.

For the purpose of this paper, the term bioenergy is used to include heat, power and biofuels. Biomass is one of the few renewable energy sources that will be used to produce all three types of energy, and potentially result in significant competition for limited resources in some parts of the country. Since biomass used for energy can grow on lands that are also valuable for food production, efficiency in biomass production and conversion need to be a fundamental consideration.

In recent years there also has been increased interest in understanding full life-cycle implication of producing bioenergy, both in terms of net energy and net greenhouse gas (GHG) emissions. Recently developed sustainability criteria are starting to address this topic, in addition to the traditional set of water, biodiversity, and other considerations.

Forestry as a Model System for Sustainability

Although all woody biomass originally comes from trees, it enters the feedstock supply chain from various places. Woody biomass feedstock can come from forest residues (tree tops, limbs and trimmed logs) generated when harvesting sawlogs and pulpwood; during forest thinning to improve growth of remaining forest stands or to reduce fire hazard; from lumber trimmings during construction and other municipal clean wood waste streams; from forest product mill residues; and from purpose-grown wood energy crops.

It is rare that a forest biomass product is produced alone. Usually, it is co-produced with a higher value product that remains in service for a long time (such as lumber in houses or furniture). Also, woody biomass is produced from managed forested ecosystems that also provide a number of co-benefits, including clean water, wildlife habitat, carbon sequestration, recreation, in addition to forest products. These same forests are also systems that are cycling carbon as part of the natural biosphere, often called the biogenic carbon cycle. When this is in balance, no new CO_2 is added to the atmosphere because forests are sequestering at a rate that is greater than or equal to what is being release through natural process and uses, such as bioenergy.

Forest products also are used in place of more energy intensive materials, such as concrete and steel. This adds complexities to the discussion of sustainability because where you draw the boundaries, time frame, and trade-offs are not always obvious.

When forest biomass is not used for energy or other purposes, there is not a simple alternative scenario. For example, future probability of insects, decay, storm damage, and fire are partially dependent on future climates. These all occur as part of the natural disturbance processes in forests. These alternative fate considerations are often ignored in life-cycle analysis because they are difficult to predict with any certainty for a specific location and time. However, they need to be part of considering sustainability in its broadest terms.

Public vs Private Forests

In the eastern United States only nine percent of the forested landscape is managed as public land, and in the west 58 percent is public land. The public lands can be managed by federal, state or local governments and have their own set of rules and regulations that reflect principles of sustainability. For private forest lands, forest landowners in some states have Forest Practices Acts or Best Management Practices that are required. Some states have also developed Biomass Harvesting Guidelines.

Over the past 20 years, a number of systems to certify sustainable forestry have developed. Larger private forest land owners and some states have adopted these voluntary certification systems (e.g. Sustainable Forestry Initiative, Forest Stewardship Council) or participate in the American Tree Farm Program. The certification is identified with products that are made from wood grown in these forests. It is a way to let consumers know that the product comes from lands where sustainable forest practices are assured using a third party monitoring system.

On federal lands, a broad range of environmental laws govern sustainability of forest management. These include compliance with laws such as the Endangered Species Act, Clean Water Act, National Forest Management Act, and National Environmental Policy Act.

Dimensions of Sustainabilty

When people talk about sustainability, it is important to ask them what they mean. The three dimensions of sustainability: economic, environmental and social considerations are important. These are briefly outlined below, with aspects that relate to biofuels.

- Economic
    - New linkages in markets – energy – food - wood products
    - Direct effects (supply, demand, cost and price)
    - Regional and international trade
    - Jobs in rural areas
- Environmental
    - Direct and indirect land use effects
    - Soil health, water quantity and quality, air quality, biodiversity and habitat, GHG emissions, genetically modified organisms and invasive species
    - Ecosystem services- co-production on a landscape
- Social
    - Regional, national, and international
    - “New Energy Economy”- renewable and advanced technology
    - Labor rights, land rights and participation
    - Energy security and food security
- Cultural and spiritual values

Also, there are major differences in the biomass feedstocks, whether they are also food and feed sources, and if they are redirecting material from other disposal options. The challenge with applying sustainability principles is developing the value proposition for bioenergy that has formal sustainability certification. In the forestry sector, the certification of forest products has been more of a market access issue, and not necessarily a willingness of people to pay more for certified products.

Challenges to Sustainability

Sustainability issues need to be addressed in the production of bioenergy as well as in the conversion processes. The dimensions of sustainability are detailed by Dale and Kline (*1*):

- Production
    - Feedstock Type
    - Feedstock Management
    - Feedstock Location
    - Feedstock Extent on Landscape
    - Environmental Attributes
    - Original Conditions of Land

- Conversion
    - Transport of Feedstock
    - Net Energy
    - Water Use
    - GHG Emissions
    - Location of Biorefinery
    - Transport to Markets

The Council on Sustainable Biomass Production (*2*) has recently released a set of sustainability criteria that could be used for voluntary certification of all non-food biomass feedstocks. The components of their criteria include: Climate Change, Biological Diversity and Productivity, Water Quality and Quantity, Soil Quality, Socio-Economic Well-being, and Integrated Resource Management Planning.

Recent laws such as the Energy Security and Independence Act of 2007 set goals for biofuels production and have attempted to address sustainability criteria indirectly by narrow definitions of what qualifies as "renewable biomass" including broad exclusions of biomass from certain types of forests. While these may be well intended, the result is that broad categories of biomass that are currently a disposal problem will not qualify if used to produced biofuels. The debate about how to assure sustainability of biofuels produced from all sources will likely continue.

Competition with Existing Products and Between Bioenergy Uses

The ability to increase bioenergy production from all sources of biomass requires a direct consideration of how compatible these new uses are with production of existing products. For example, scientists are exploring ways to produce biofuels as part of the process of making paper from wood. Producing heat and power from mill residues has been a long term practice at forest products industries, and is a major part of our domestic renewable energy portfolio. The collection and utilization of logging residues that historically were left in the forest represents a large and currently under-utilized source of biomass. In agricultural systems, using corn cobs and stover can be added to the system that produces biofuels from corn, either as thermal process energy or as separate cellulosic biofuels process.

Our models of supply and demand for bioenergy feedstocks need to be more directly linked to price of fossil fuels they replace (such as petroleum) so that we can better understand how different incentives and market forces interact.

Summary

Producing biofuels that “make sense” and meet sustainability concerns can take many forms. In general it makes sense when bioenergy uses material that otherwise would have negative environmental consequences, is produced on marginal lands with minimal inputs, has production scaled to match local feedstock availability, is compatible with maintaining working landscapes, and that has favorable net energy and net greenhouse gas profiles.

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Chapter 7

Algal Technologies for Biological Capture and Utilization of CO_2 Require Breakthroughs in Basic Research

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To fully offset the carbon emitted from anthropogenic sources, taking into account the 55% that are captured by enhanced biological and physical processes in the global carbon cycle, an additional 4 Gigatons (Gt) of carbon must be captured per year, and that number is likely to increase. Options for technology that can capture such an immense amount of carbon in the near term are limited. There are real opportunities for achieving significant reductions in CO_2 emissions in the algal field but the current state of research is still very much in the realm of basic science and much needs to be done before we can think about it in technological terms. Biological capture by photosynthetic microbes is an attractive technology because it is renewable, scalable, and may be used to produce fuels and chemicals cheaply. Identification of novel, robust strains, and breakthroughs in bioreactor design and harvesting/extraction technology, are necessary to realize this goal. This chapter, and the workshop from which it is derived assesses the productivity and carbon capture capacity of photosynthetic microbes and outlines the areas in which there are opportunities to achieve significant reductions in CO_2 emissions.

Introduction

The estimated anthropogenic contribution to the carbon cycle in the form of CO_2 released into the atmosphere is approximately 9 Gigatons (Gt) per year. Approximately 7.6 Gt of this is from fossil fuels and 1.4 Gt from land-use change. While as much as 55% of this carbon is absorbed by natural processes, up to 4 Gt are deposited in the atmosphere every year (*1*).

As much as 65% of this anthropogenic contribution to atmospheric carbon comes from large stationary sources globally, many of these being coal fired-power plants that provide the base-load of electricity demand. In the U.S., these sources supply 60% of electricity and this demand is expected to grow over the next 20 years. If coal is to remain the primary resource for electricity generation in the U.S., carbon emissions are also set to grow.

By the year 2025, 100 GW of new coal-fired steam electricity is expected to be online in the U.S. alone. New plants are expected to be more efficient, making use of integrated gasification combined cycle (IGCC) technology, however the U.S. will still likely rely on the existing fleet of pulverized coal fired power plants as well. These currently supply the base-load electricity, 320 GW capacity and 1,900 billion Kilo-watt hours per year, which is difficult at this time to replace completely by renewable resources.

Carbon capture and storage (CCS) technologies can be used to mitigate these carbon emissions that would otherwise be released to the atmosphere. CO_2 generated in concentrated streams by the combustion of fossil fuels, as in the flue gas from power plants and exhaust gas from cement and steel manufacturing processes, can be captured and sequestered. Additionally, some CCS technologies can capture and sequester atmospheric CO_2. The prevalent use of coal combustion for electricity generation is driving much of the demand for CCS technologies, however some estimates predict the costs of CCS technology to be economically attractive only after the year 2030, making implementation at a large scale unlikely in the near term (*2*).

Photosynthetic biological systems have the potential to make a significant impact in the carbon capture area. In particular, photosynthetic microbes are an attractive option for biological CCS because they have the ability to capture CO_2, and use the energy in sunlight to store this carbon in forms useful to humans such as fuels, food additives, and medicines. The fact that many algae can have a doubling time of as little as 4 hours makes accumulation of biomass and production of useful molecules realistic on an industrial scale.

To use algae as a carbon capture technology however, a number of important limitations need to be overcome.

Current designs for amine scrubbing for removal of CO_2 from flue stream of coal-fired power plants assume that 90% of the CO_2 is removed (*3*). Algae would need to have the ability to capture as much CO_2 as current CCS technologies are projected to, at similar costs. If less CO_2 is captured by algal technology than by current CCS tecnologies the costs must be significantly lower. The production of biofuels and high value bioproducts would offset the costs of implementing biological organisms as a carbon capture technology as it would in the case of other CCS technologies when fuels are synthesized from the captured CO_2.

Much basic research has been carried out on algae as a production system for fossil fuel alternatives including diesel-like polymers, methane and hydrogen. The U.S. government funded 25 years of research under the Aquatic Species Program (ASP) at the National Renewable Energy Laboratories (NREL), a program that was wound down in 1996, due to lowered price of oil. This research effort led to the isolation of roughly 3000 species of algae that might be useful in this regard (*4*). Most of these have been lost over the years due to the absence of culturing necessary to propagate these species. Approximately 300 of these strains have survived and NREL is revisiting the project. Additionally, recent financial investments from the private sector into research towards deployment of algae as a fuel production system indicate that this technology is near the point of profitability. The success stories so far have come mostly from companies producing both fuels and high value products.

As yet, we do not have the means to displace liquid transportation fuels, at scale, with a renewable and sustainable resource. Neither can we capture all of the carbon emitted from stationary fossil fuel sources, by current carbon capture and sequestration methods. The use of algae cultured in non-oceanic environments to capture emissions directly from fossil fuel sources could be a technology that aids in the inexpensive reduction of CO_2 emissions from the energy sector over the coming decades. The ultimate carbon emissions associated with deployment of such a technology would depend on the capacity and efficiency of the algae to capture the carbon and on the use of the stored carbon after capture. When the algae or derived oil is combusted, this stored carbon is again released to the atmosphere. The associated emissions, however, would be offset in part by the algae growth that led to their production, potentially leading to an overall decrease in the amount of anthropogenic carbon released relative to using a fossil source.

Algae produced in this way could be valuable in providing a source for energy dense liquid fuel production not matched currently by other means. The oils derived from algae can be used to produce energy dense fuels such as those used in aviation. Already examples exist where biofuel from algae has been used to power a passenger jet. To meet this demand with another fuel type would be difficult due to the need for a fuel with equivalent energy density to the fossil fuel fuel used currently.

This review discusses the material presented at a workshop held on September 2009 at Washington University in St. Louis. The workshop brought together experts in photosynthesis, bioenergy, microalgae, coal and carbon sequestration to discuss opportunities and challenges in biological CO_2 capture and utilization. The following sections present and discuss these findings and highlight nine game-changing improvements that could enable algae as a carbon capture technology. References to outside and existing literature are made where appropriate to support and help further explain some of the findings.

Game-Changing Technological Improvements

Improvements in delivery, capture, and the metabolic transformation of carbon dioxide into industrially relevant molecules are necessary before algae can be used on a globally significant scale. We feel that the ten topics below are where the largest gains can be made in the near future towards technologies that biologically capture greenhouse gases from fossil fuel sources and contribute to the global energy system.

- Carbon Dioxide Uptake and Utilization
- Light Harvesting Efficiency
- Maximize Biomass Production
- Biofuel/Bioproduct Production
- Bioprospecting and Development of Robust Strains
- Bioreactor Design
- Harvesting and Extraction
- Water Use Efficiency
- Integrated Power Plant Design
- System Analysis

The key limiting factors that can be targeted within each of the above topics are discussed in the following sections.

Overview of Photosynthesis, Carbon Capture, and Fixation

Algae capture CO_2 and fix it into carbon molecules using photosynthetic processes similar to land plants. The amount of solar energy reaching the earth far exceeds current human energy demand. Photosynthetic organisms have the capacity to harvest a portion of this energy and store it in the form of reduced carbon that can be utilized for both energy and be converted into useful products (Figure 1). There are, however, significant thermodynamic limits imposed on the photosynthetic conversion of sunlight to reduced carbon. The numerous reactions needed to facilitate this process inevitably lead to losses in efficiency.

Photosynthesis begins with absorption of particular wavelengths of light by specialized pigment-protein complexes native to the organism (Figure 2). This absorbed light energy is quickly converted into chemical energy carriers such as NADH and ATP, which fuel subsequent steps in biological carbon capture and fixation. Photosynthetic efficiency is the fraction of total solar radiation that is converted into chemical energy during photosynthesis (Equation 1).

$$2H_2O + CO_2 + \text{energy} \dashrightarrow CH_2O + H_2O + O_2 \qquad (1)$$

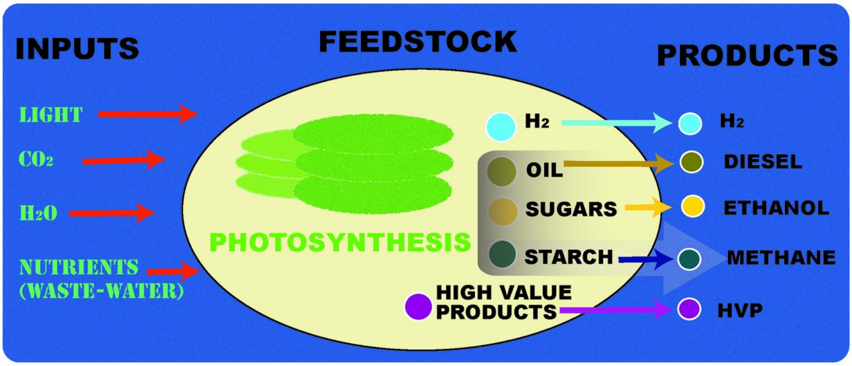

Figure 1. Overview of inputs and outputs of photosynthesis in algae. Light, CO_2 and water are utilized by the photosynthetic reactions to produce valuable products such as hydrogen (H_2), oil (including triacylglycerols, TAGS), sugars and starch. H_2 can be utilized as a fuel or light energy carrier in fuel cells. High value products (HVP) can be made to supplement costs and include products such as carotenoids, antibodies or commodities such as organic acids. Legend courtesy of Ben Hankamer, The University of Queensland, Australia.

Photosynthetic efficiency is affected by several physical parameters: light intensity, partial pressure of oxygen and CO_2, temperature, pH and nutrients. However, the degree to which each of these parameters affects a system varies and in some cases will be different between aquatic and terrestrial species.

When all of the losses are summed, the maximal theoretical limit for photosynthetic efficiency at this stage for plants is between 4.6% and 6% for C3 and C4 plants, respectively, and 8% for microalgae (Figure 3). C3 and C4 plants are distinguished based on metabolism of CO_2. In C3 plants CO_2 is fixed directly into the three-carbon intermediate 3 phosphoglycerate, whereas in C4 plants CO_2 is fixed into a four carbon organic acid that is concentrated in specialized carbon fixing tissues. The highest reported efficiencies for C3 and C4 plants is about 40% and 60% of the maximum, however, average crop yields fall far below this number (*5*, *6*). Assuming a C3-like metabolism for photosynthetic microbes and minimization of photorespiration by enriching the atmosphere with CO_2 from flue gas, the theoretical efficiency of photosynthesis is 10.6% (from Marcel Janssen, *unpublished*). In the short term, increasing maximum efficiency may be difficult. During the workshop several interesting ways to increase the maximum efficiencies were discussed and some of these are described under "Light Harvesting Efficiency".

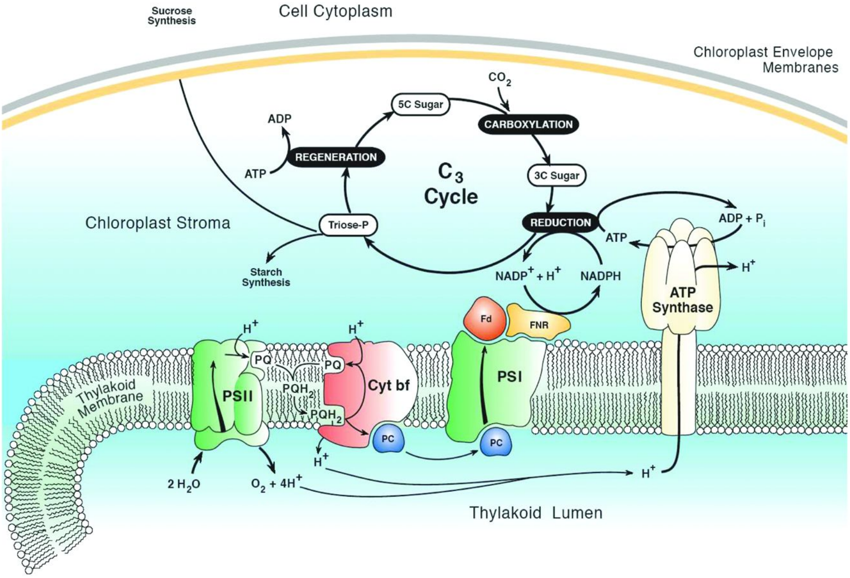

Figure 2. Overview of oxygenic photosynthesis and carbon fixation by the Calvin Cycle. Light driven water oxidation by photosystem II (PSII) releases protons into the lumen and generates O_2, electrons and protons. The protons are utilized by ATP synthase for ATP production. The electrons are shuttled through the electron transfer chain through the light driven protein complex, photosystem I (PSI), to ferredoxin (Fd). Finally, ferredoxin-NADP reductase (FNR) mediates reduction NADP to form NADPH, a soluble reducing equivalent. The Calvin Cycle (C3 cycle) involves three phases: CO_2 fixation by RuBisCO, followed by reduction using NADPH and ATP and finally regeneration of precursors. Figure courtesy of Don Ort, University of Illinois Urbana-Champaign.

Many factors influence the rate of photosynthesis including light intensity, CO_2 concentration, mass transfer of CO_2 into liquid, temperature, and availability of nutrients. Additionally, the amount of ribulose 1, 5-bisphosphate carboxylase oxygenase (RuBisCO) present in a cell represents an intrinsic limit in the rate of carbon fixation. Other less energy intensive carbon fixation pathways exist in biological organisms and possibly can be used to make the process more efficient. The following sections discuss these factors in more detail.

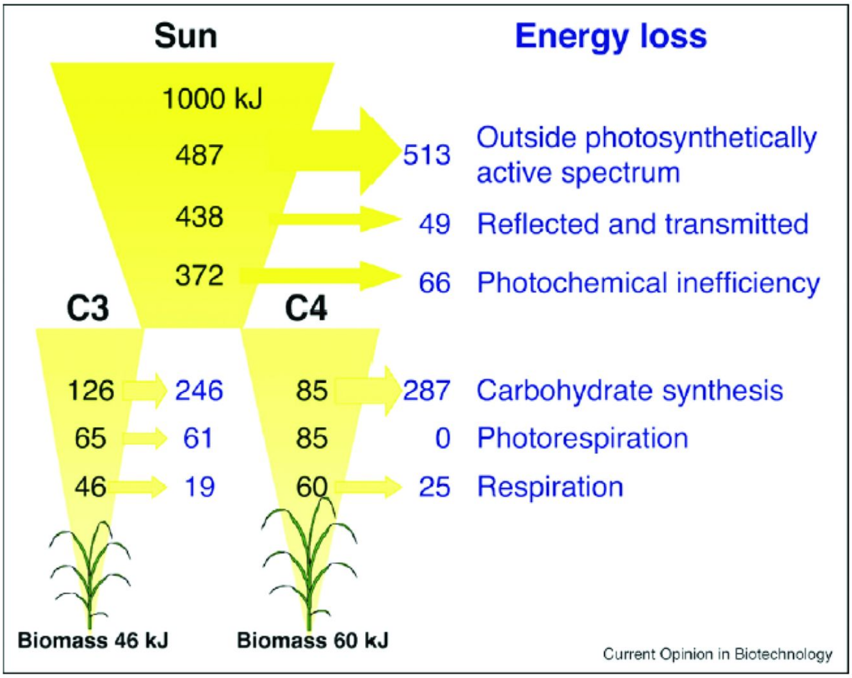

Figure 3. Maximum Theoretical Photosynthetic Efficiency in Plants and Microalgae. C3 and C4 plants have a maximum theoretical yield of 4.6 and 6.0%. Maximum reported yields are 50-60% of theoretical yields, but average yield is 1%. Reproduced with permission from reference (5). Copyright 2008 Elsevier.

Carbon Dioxide Uptake and Utilization

As oxygenic photosynthetic organisms, algae are well adapted to capturing ambient CO_2. Growing algae to capture ambient CO_2 will remove carbon dioxide and store it in the form of biomass. Depending on the use of the accumulated biomass, products derived from this process are at best carbon-neutral. Some studies suggest that a 1MW plant facility producing 8323 metric tons of CO_2, or 2269 metric tons C would require a 16 hectare algal bioreactor facility algal facility yielding 80 g dry weight m^{-2} day^{-1} or a 64 hectare algal facility yielding 20 g dry weight m^{-2} day^{-1} (Ben Hankamer, *unpublished*).

Bringing a concentrated source of CO_2, such as the flue gas from a power plant, into contact with algae to increase capture efficiency and productivity has its challenges. Efficiently capturing carbon dioxide from an elevated CO_2 source depends on many factors, but one of the most limiting at present is the ability of the algae to capture and fix carbon at a sufficient rate to avoid acidification of the medium (and thus crash of the culture). Due to this, research is under way to isolate and engineer strains that are tolerant to high CO_2 levels, and are effective at removing large quantities of CO_2 in one pass.

Historically, establishing the limits of carbon uptake and fixation in microalgae represented a major challenge. Green algae can grow at CO_2 concentrations ranging from <=0.01% to > 0.5%. Recent findings in *Chlamydomonas* indicate that there are typically three tiers of CO_2 concentrations within this range that have distinct carbon concentrating mechanisms (CCMs): very low (< = 0.01%), low (0.03 – 0.4%), and high (> or = 0.5%), (Martin Spalding, *unpublished*). Ambient CO_2 is at 0.038%. Understanding the differences in CCM that allow strains to flourish at these three levels is needed in order to improve CO_2 fixation.

In addition to the efficiency losses due to carbon delivery to the cell, another well-documented efficiency loss occurs at the cellular site of carbon fixation: RuBisCO. This is due to the fact that there is a secondary oxygenase activity in RuBisCO, which represents a major waste of cellular resources. Ongoing efforts to improve algal carbon uptake efficiency at various CO_2 concentrations are discussed.

Ambient CO_2 Concentrations

At ambient CO_2 concentrations (385 ppm), microalgae growing in full sunlight can become carbon-limited. In this scenario the rate of carbon uptake and utilization in the culture exceeds the mass transfer of CO_2 from gas into the media. Significant cellular energy in microalgae is devoted to concentrating and importing CO_2. In addition, many enzymatic steps are needed to complete the Calvin Cycle leading to reduced carbon building blocks utilized by downstream processes. In order to improve algal CO_2 absorption, ongoing research seeks to grow microalgae with modified carbon concentrating mechanisms and alternative CO_2 utilization pathways.

Elevated CO_2 Concentrations

From a technological point of view it is possible for microalgae to capture carbon from the flue gas emitted from stationary fossil fuel powered sources. Some of the limiting factors identified by various studies are the relatively large land area required, the ability to capture only 25 to 30% of CO_2 in one pass from a flue stream, the cost of pumping the flue gas, and the undeveloped state of this technology (*7*).

There are many fundamental questions that still need to be answered regarding microalgal growth at elevated CO_2 concentrations. The most critical determination is the maximum amount of CO_2 sequestered from a given concentration of input gas. There is debate as to the actual amount of CO_2 that can be removed from the input stream. Data presented by Martin Spalding suggested that less than 5% of the CO_2 can be removed from a stream containing >1% CO_2 if the cells are only at a modest density (Figure 4). However, work of others suggests that as much as 70% uptake from a 2% CO_2 stream could be achieved in the blue-green algae, cyanobacteria, which are the largest group of oxygenic photosynthetic prokaryotes. Further results indicate that the maximum amount of CO_2 sequestered from a given concentration of input gas could be 100%. The determination of this limit depends on many factors including the design of the photobioreactor, bubble diameter, bubble lifetime, and culture density (Lada Nedbal, *unpublished*). Other important factors contributing to the uptake include the pH of the media and the tolerance of the organism to high CO_2. The wide range of values necessitates further research into this key component of carbon capture.

At both ambient and elevated CO_2 concentrations there are important issues to consider when growing algae for the purpose of CO_2 capture and high productivity. The following sections discuss some of these aspects and avenues for potential research opportunities that may lead to increased efficiencies of CO_2 uptake.

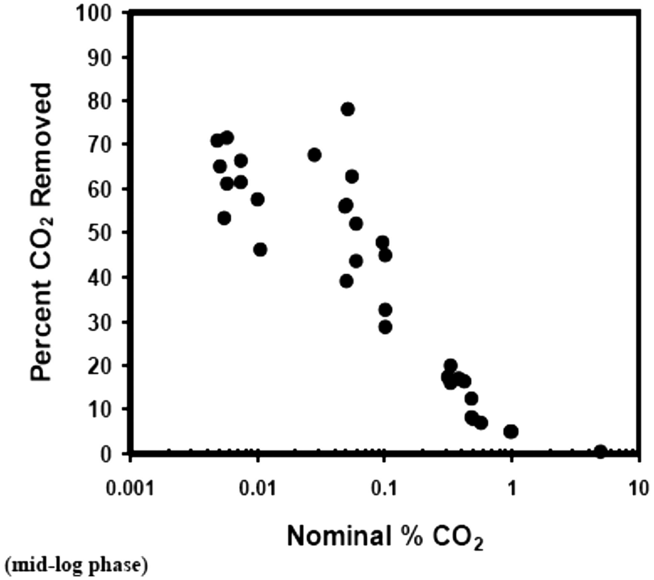

Figure 4. The percentage of CO_2 removed from the incoming bioreactor gas stream by a mid-log phase (~1-2x106 cells/ml) Chlamydomonas culture over a range of incoming CO_2 concentrations (nominal % CO_2). Each data point represents an independent cell culture. Reproduced with permission from reference (8). Copyright 2005 NRC Research Press.

Mass Transfer

The mass transfer of carbon dioxide from air into the media can be growth-limiting in dense algal cultures. As discussed above, the transfer of CO_2 from a gas to a liquid depends on many parameters. The gas flow rate, CO_2 partial pressure and bubble diameter and lifetime in particular can have large influences on the rate of transfer.

Water chemistry also influences the solubility of CO_2 and therefore, to a small extent, the transfer capacity. CO_2 can be dissolved in water according to Henry's law and, to a small extent, reacts with water to form carbonic acid (H_2CO_3). The equilibrium shifts towards HCO_3^- (bicarbonate) as the pH increases to a neutral range. HCO_3^- is actively transported into microalgae while CO_2 enters the cell by passive diffusion (Figures 5 and 6). The pH of the media plays a major role in mass transfer and can drastically alter growth dynamics of the organism. Controlling pH by the addition of buffering agents can therefore affect mass transfer of CO_2 and carbon uptake by the algae.

Carbon Concentrating Mechanisms

Genetic modification of CCMs may improve the energetic efficiency and rate of carbon uptake in oxygenic photosynthetic organisms. Green algae and cyanobacteria have evolved mechanisms to uptake and concentrate inorganic carbon from the environment (Figures 5 and 6). The strategy utilized depends on the form of carbon encountered. Conversion of CO_2 to HCO_3^- in an aqueous environment is pH dependent, with basic environments promoting formation of HCO_3^-. Within the cell, enzymatic interconversion takes place in order to transport and concentrate CO_2 at the place of carbon fixation in the chloroplast pyrenoid in green algae or carboxysome in cyanobacteria. Elucidation of the components of both prokaryotic and eukaryotic carbon concentrating systems is underway (Lou Sherman, *personal communication*). This will allow for the generation and isolation of mutants with enhanced uptake capacity. There is, however, an energetic cost to operate CCMs. This can be circumvented by growing the algae at high CO_2 concentrations, where a CCM is likely unnecessary.

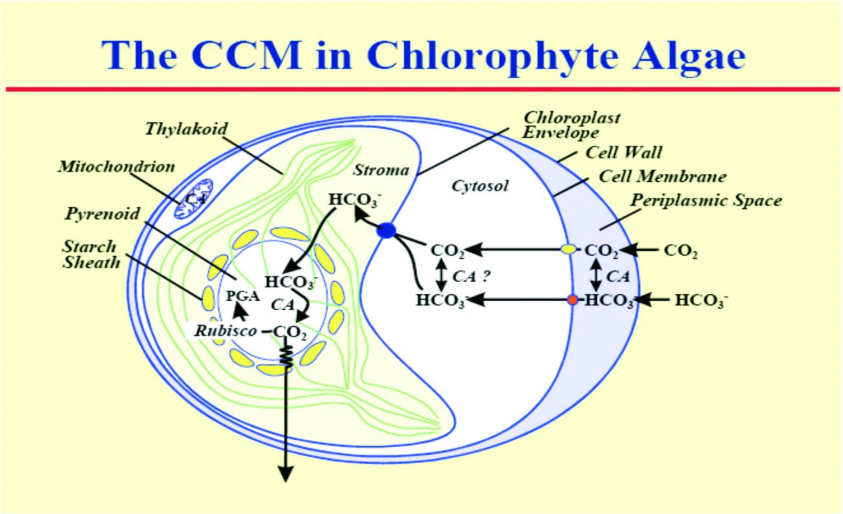

Figure 5. CO_2 concentrating mechanism in a green alga. Bicarbonate (HCO^{3-}) is transported into the chloroplast and converted into CO_2 by carbonic anhydrase (CA) to provide substrate CO_2 for RuBisCO in the pyrenoid, the site of carbon fixation. Reproduced with permission from reference (9). Copyright 2006 Springer.

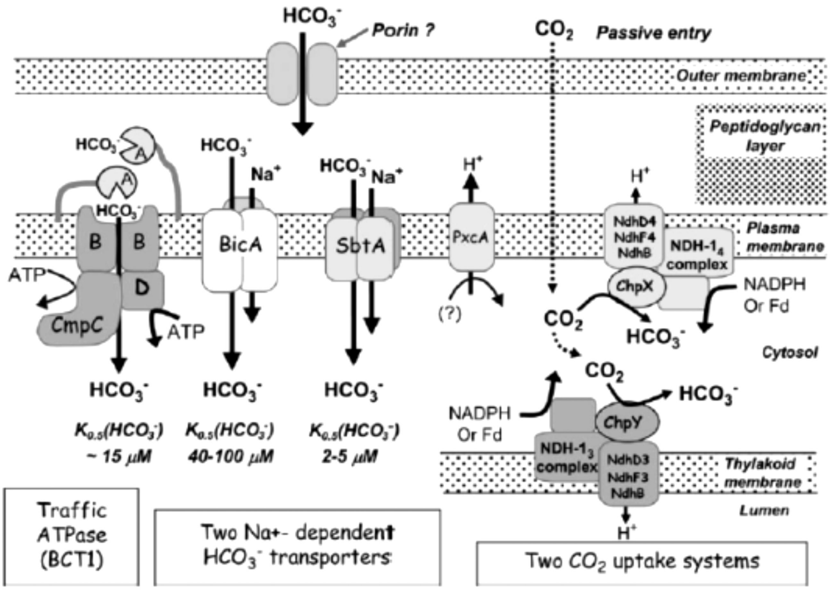

Figure 6. Carbon transport in Cyanobacteria. Bicarbonate (HCO^{3-}) is actively transported across the membrane using multiple mechanisms tuned to substrate availability. Once internalized, CO_2 is then concentrated in the carboxysome, a bacterial subcompartment housing carbon fixation enzymes. Reproduced with permission from reference (10). Copyright 2008 Oxford University Press.

Increasing Efficiency of the Calvin Cycle

In oxygenic photosynthetic organisms, CO_2 is fixed in the Calvin Cycle by RuBisCO. Substantial losses to photosynthetic efficiency lie between initial charge transfer reactions of photosynthesis and downstream carbohydrate biosynthesis. Depending on the mechanism utilized to fix carbon and the amount of ATP and NADPH utilized, and assuming total incident radiation including infra-red, the maximal theoretical efficiency at this stage (including light capture and energy transduction) is between 8 and 13% before losses due to photorespiration and respiration (*5*).

CO_2 and O_2 are both substrates of RuBisCO. Fixation of CO_2 results in 2 molecules of 3-phosphoglycerate (3-PGA), while fixation of O_2 results in the production of 3-PGA and 2-phosphoglycolate (2-PG), (*13*). 3-PGA is an intermediate in the reductive C_3 cycle for production of intermediates in biosynthesis and energy production and also for regeneration of Calvin Cycle intermediates. The byproduct of O_2 fixation, 2-PG cannot be utilized by the reductive C_3 pathway and therefore must be recycled to recover the carbon through the photorespiratory C2 cycle (*13*). Photorespiratory metabolism inherently decreases carbon fixation efficiency, and estimates are that at current atmospheric CO_2 concentrations, for every three carbons fixed, one oxygen molecule is fixed. To minimize photorespiration, plants have evolved mechanisms to increase CO_2 concentrations by spatially separating primary CO_2 fixation and RuBisCO activity (C4 plants) or by temporally separating photosynthesis and carbon fixation (CAM plants). Metabolism of CO_2 in C4 and CAM plants is similar, but in contrast to C4 plants, CAM plants use CO_2 that is collected at night and stored as malic acid, allowing stomata to remain closed during the day to conserve water.

Algae and cyanobacteria have evolved efficient carbon concentrating mechanisms in order to reduce the oxygenation reaction (Figures 5 and 6). By actively transporting carbon to the site of carbon fixation, photorespiration is reduced due to the increased ratio of carbon to oxygen. Several C2 pathways to efficiently recycle 2-PG and recover CO_2 have evolved in algae and cyanobacteria (Figure 7).

Because the oxygenase activity of RuBisCO leads to decreased productivity, there has been interest in modifying the enzyme's catalytic properties. Simultaneous enhancement of RuBisCO specificity and catalytic rate has been a scientific goal for a long period of time because of implications for yield in crop-producing plants. However, active site modification of the RuBisCO enzyme has led to the discovery that catalytic rate and specificity are inversely related (Figure 8). RuBisCO may already be optimized and further modifications may not improve function (*12*). While increasing enzymatic catalysis may be difficult, there has been interest in modifying Calvin cycle protein levels to increase recycling of intermediates and CO_2 incorporation. This is an active area of investigation.

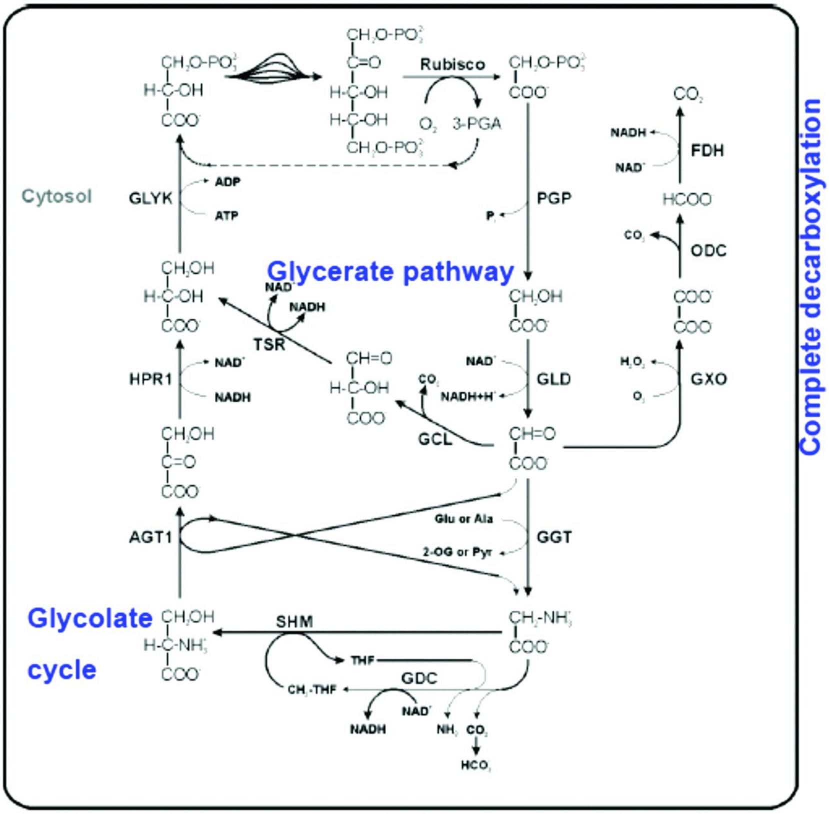

Figure 7. Cyanobacteria use a plant/bacterial-like photorespiratory pathway. Phosphoglycolate generated as a byproduct of RuBisCO oxygenase activity is metabolized using several pathways. Schematic drawing of the complete photorespiratory 2-PG metabolism in cells of Synechocystis sp. strain PCC 6803. 2-PG metabolism is branched into three routes: plant-like glycolate cycle, bacterial-like glycerate pathway, and complete decarboxylation branch (PGP – 2-PG phosphatase, GLD – glycolate dehydrogenase, GGT – glycine/glutamate aminotransferase, GDC – glycine decarboxylase, SHM – serine hydroxymethyltransferase, AGT1 – alanine/glyoxylate aminotransferase, HPR1 – hydroxypyruvate reductase, GLYK – glycerate kinase, GCL – glyoxylate carboligase, TSR – tartronic semi-aldehyde reductase, GXO – glyoxylate oxidase, ODC – oxalate decarboxylase, FDH – formate dehydrogenase). Reproduced with permission from reference (11). Copyright 2010 Springer.

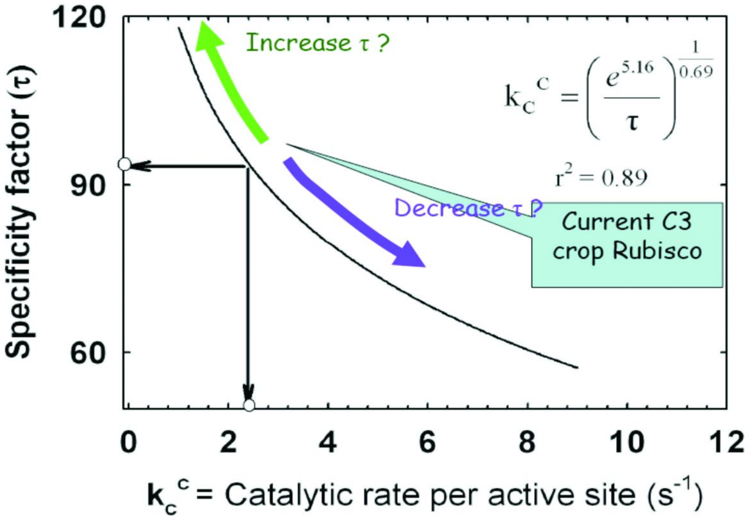

Figure 8. Trade-off between RuBisCO specificity and catalytic rate. Carbon fixation competes with photorespiration because CO_2 and O_2 are both substrates for RuBisCO. The oxygenase activity is not desirable as it leads to losses in carbon fixation. Analysis of the natural genetic variation in the kinetic properties of RuBisCO from divergent photosynthetic organisms reveals that forms with higher specificity factors have lower maximum catalytic rates of carboxylation per active site, and vice versa. This inverse relationship implies that higher specificity factors would increase light-limited photosynthesis, while the associated decrease in catalytic rate would lower the light-saturated rate of photosynthesis. The daily integral of CO_2 uptake by a crop canopy is determined by a dynamic combination of light-limited and light-saturated photosynthesis. At current atmospheric CO_2 levels the average specificity factor of current C3 crops exceeds the level that would be optimal for the present atmospheric [CO_2] of >380 ppm but would be optimal for ~220 ppm, which is close to the average of the last 400,000 years prior to the Industrial Revolution. Canopy simulations reveal that 10% more carbon could be assimilated by C3 crops if they were operating with a C4 RuBisCO and this advantage would grow as atmospheric CO_2 levels continue to increase (5, 6). Figure courtesy of Don Ort, University of Illinois Urbana-Champaign.

Secondary Pathways

Diverse carbon capturing pathways have evolved to sustain biomass production in a variety of environments. Several of the limits to carbon fixation using the Calvin cycle native to microalgae have been discussed. In addition to the Calvin cycle, four additional CO_2 fixation routes have been identified (Figure 9). While several of these pathways require anoxic conditions due to the O_2 sensitivity of some of the enzymes, others can occur during aerobic metabolism. Of particular interest, the 3-hydroxypropionate pathway utilizes the enzymes acetyl-CoA carboxylase and propionyl-CoA carboxylase to fix CO_2 into glyoxylate, an intermediate in carbon metabolism. Genetically engineering alternative CO_2 fixation strategies might be advantageous because they may avoid the regulatory constraints and substrate limitations of native pathways.

A detailed understanding of the diverse mechanisms and pathways for carbon fixation will facilitate an integrated approach for maximal biological carbon uptake. It may be possible to incorporate multiple distinct pathways into a single organism to enhance carbon sequestration. Furthermore, these studies may lead to the development of novel pathways for carbon fixation that do not exist in nature.

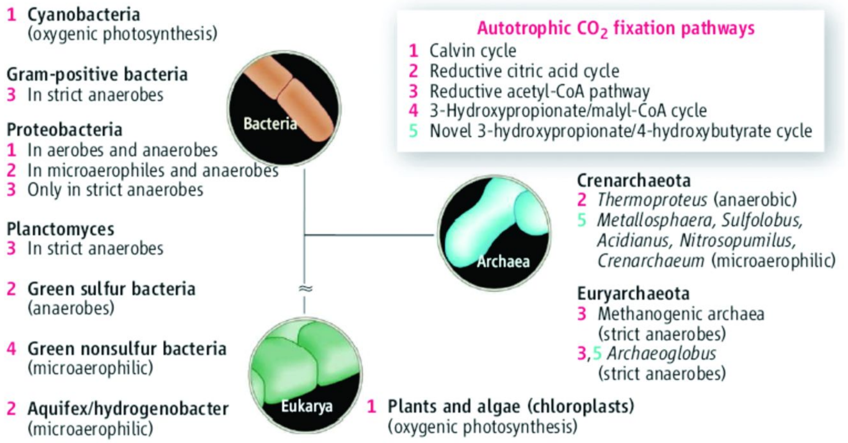

Figure 9. Autotrophic Carbon Fixation Pathways. Most photosynthetic organisms can grow autotrophically using only CO_2 as a carbon source. Plants, algae, cyanobacteria and photosynthetic proteobacteria use the Calvin cycle (pathway 1) to fix CO_2. The green sulfur bacteria use the reductive citric acid cycle (pathway 2), while green nonsulfur bacteria use the 3-hydroxypropionate cycle (pathway 3). The other pathways shown are known only in nonphotosynthetic organisms. Reproduced with permission from reference (14). Copyright 2007 Science.

Light Harvesting Efficiency

As discussed previously, photosynthetic efficiency is the fraction of total solar radiation that is converted into chemical energy during photosynthesis (Equation 1), and the highest reported values are about 40% and 60% of the maximum for C3 and C4 plants, respectively (*5*, *6*). Components of this include the biochemical pathways that involve carbon uptake, fixation and metabolism, and potential ways to improve these were dicussed in the previous sections.

Another component that determines overall photosynthetic efficiency is the light harvesting ability of the algae. In the short term, increasing the maximum efficiency of this may be difficult but during the workshop several interesting ways were identified and are discussed in the following sections.

Modification of Antenna Complexes

One major limitation to photosynthesis in full sunlight is that photosynthetic reaction centers quickly become saturated (Figure 10). At low light intensities, in the morning and evening, and in shaded environments, photosynthetic activity increases linearly with light intensities. However in the middle of a sunny day, photosynthetic organs or organisms exposed to full sunlight become saturated and must dissipate this excess energy by non- photochemical means.

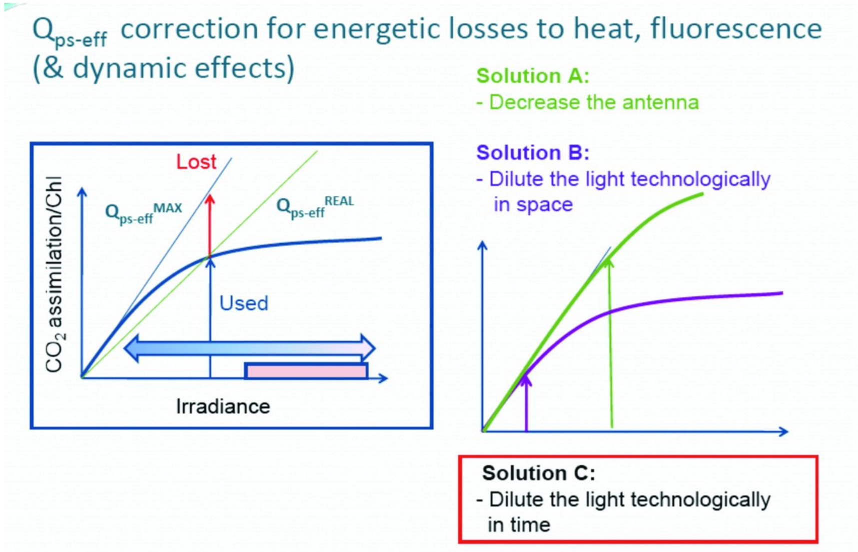

Figure 10. Losses in photosynthesis with increasing light intensity and possible ways to overcome the loss. Qps-eff is photosynthetic efficiency. At high light intensity, photosynthetic antennae complexes dissipate excess energy as heat and fluorescence, leading to less light utilization. To overcome this limitation, one could decrease antennae size, or dilute the light spatially or temporally. Figure courtesy of Ladislav Nedbal, Institute of Systems Biology and Ecology, Academy of Sciences for the Czech Republic.

In aquatic photosynthetic organisms, light saturation in full sunlight is enhanced by the large antennae complexes that are used to harvest light at low intensity that occurs during self-shading in high density cultures. At high light intensity, light harvesting ability exceeds photosynthetic electron transport capacity. Instead of direct transfer to reaction centers, excess energy is dissipated in the form of heat. These mechanisms have evolved to reduce the formation of reactive oxygen species generated as a byproduct of photosynthesis. Research suggests that in dense cultures of aquatic photosynthetic organisms, fine-tuning the antenna size can increase overall biomass yield, which will facilitate carbon capture (Figure 10 and 11).

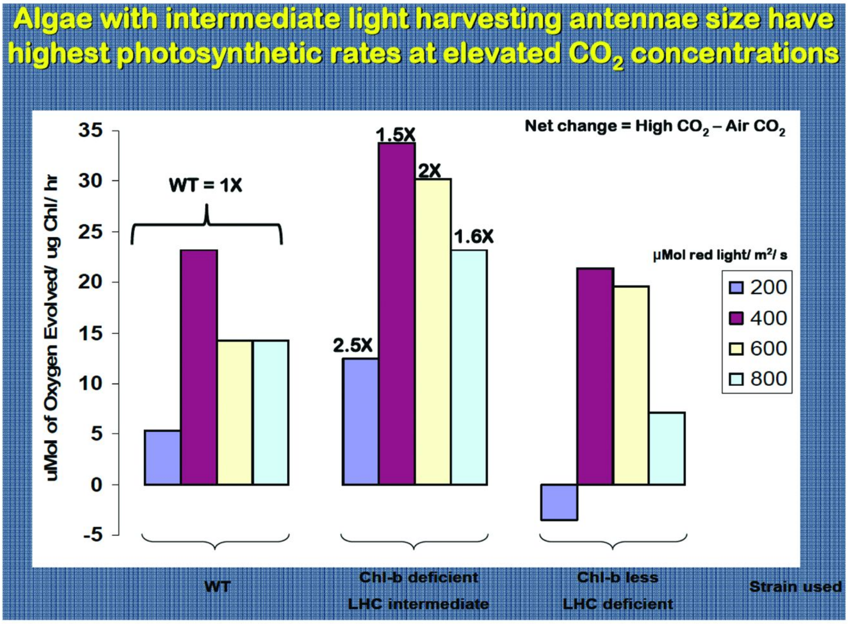

Figure 11. Photosynthetic rates in algae with varying antennae size. Photosynthetic activity was measured in algae strains with reduced antennae or lacking antennae in air and in high CO_2 at various light intensities. WT, represents wild type, unmodified algae strain; Chl-b deficient is a chlorophyll b deficient algae strain with intermediate light harvesting antennae/complex size (LHC); Chl-b less, represents algae strain with less chlorophyll b than wild type and deficient in LHC. Photosynthetic rates are expressed as the photosynthetic rate in the presence of 10 mM Na bicarbonate minus the photosynthetic rate in air. Figure courtesy of Richard Sayre and Zoee Perrine, Donald Danforth Plant Science Center and Phycal Inc., St. Louis, respectively.

Increasing Photosynthetically Active Radiation (PAR)

Another major loss in efficiency is due to the amount of the solar radiation that can be absorbed by photosynthetic pigments. Over half of the solar radiation impacting the earth is outside the range of photosynthetically active radiation (PAR) (400-740 nm). There are additional losses within this spectrum due to reflectance and transmittance of green light. Furthermore, losses due to photochemical inefficiency in the form of heat also represent a substantial fraction. Therefore, even before carbon fixation takes place, approximately 60% of the energy available in total solar radiation is not harvested (*5*, *6*).

Increasing the spectrum of solar radiation captured by photosynthesis increases the potential maximal efficiency. Biotechnology and physical science each have promising solutions to this problem. First, it is important to note that the capacity to increase the amount of harvestable sunlight has already evolved in one particular organism, *Acaryochloris marina*. This organism contains a novel chlorophyll molecule, chl-d, that exhibits a red shifted absorption spectra, extending the photosynthetically active radiation for this organism approximately 40 nm compared to plants, microalgae and related cyanobacteria. Transferring enzymes capable of producing chl-d into other organisms may have the ability to increase the amount of usable wavelengths in the solar spectrum, potentially increasing the maximum efficiency by as much as 5% compared to organisms with only chl-a.

Another way to increase the amount of sunlight that can be utilized is to use materials or chemicals with the ability to shift the wavelength of light from a non-usable wavelength to one that the reaction centers can use. There are many materials capable of shifting light from a short wavelength, high-energy light to a longer wavelength, lower energy light. In fact, this Stokes shift is commonly seen in fluorescent molecules. One target would be to shift green light to red light. This could significantly increase the total amount of photosynthetically active radiation and therefore increase efficiency.

Maximize Biomass Production

Microalgae are attractive for biofuel production because for some species the biomass doubling times are in the range of 4 to 24 hours. Additionally, there are strains that contain up to 80 percent oil by dry weight (*15–17*). The accumulation of high biomass over a short time period is desirable and indeed may be essential for making algal culture a viable option for contributing to the energy supply. Currently, ongoing research seeks to confer short doubling times upon strains, and increase yield of high value products from the resulting biomass.

Algae can grow in the presence or absence of light. In the absence of light some algae can grow heterotrophically, using reduced carbon skeletons, such as glucose, as substrate. In this mode of growth, the growth rate is much higher than it can be when algae grow in the presence of light. Under optimal conditions, the maximum photoautotrophic (fueled by sunlight only) growth rate (μ_{max}) is only half that of heterotrophic bacteria because of major differences in the allocation of cellular resources (*18*).

During photoautotrophic growth, as much as 30% of the total cellular protein is allocated to the processes of photosynthesis and carbon fixation. Typically, RuBisCO accounts for 10% of total protein content of these cells and the apoproteins in the photosynthetic apparatus account for up to 20% (*19*). Additionally, compared to heterotrophs, photoautotrophs have only about half as much of the machinery necessary to make monomers for DNA, RNA, and protein synthesis, and for polymerizing the resulting monomers on an equal cell volume basis. A generalized equation for the specific growth rate of an alga can be expressed in terms of the maximum specific reaction rate *R* of a catalyst *i* (e.g.

enzyme, transporter, redox agent, pigment-protein complex), and a factor *F* for the fraction of this reaction rate needed to account for the observed growth rate, with *F* varying as a function of environmental factors such as inorganic carbon and light supply. The growth rate hypothesis resulting from this observation is valid for about half of algal species, and says: μ (specific growth rate) is a linear function of rRNA content, with a constant specific reaction rate of rRNA at all rRNA contents (Equation 2).

$$\mu = B_i \bullet C_i \bullet R_i \bullet F_i \quad (2)$$

Where μ = specific growth rate (mol C assimilated • mol C in cell^{-1} • s^{-1}); B_i = mol of catalyst of essential reaction i • mol C in catalyst; C_i = mol C in catalyst • mol C in cell-1; R_i = maximum specific reaction rate of the catalyst of reaction i with the reaction product scaled to units of mol C from mol C of product per mol cell C (mol C transformed • mol catalyst^{-1} • s^{-1}); F_i = fraction of potential R_i in cell needed to account for observed μ.

Algae grown photomixotrophically, where they use not only endogenous but exogenous carbohydrates as an energy source, show a higher μ_{max} than when grown photoautotrophically, but the cost of resulting fuel is increased because of the added cost of reduced carbon sources. Additionally, photomixotrophic growth has many implications for greenhouse gas emissions depending on how the feedstock that provides the reduced carbon was grown, obtained and processed. Growing cultures solely under heterotrophic conditions would also preclude the direct capture of carbon dioxide from fossil fuels sources. Aside from growth on waste carbon sources or in a two-stage production method (See Biofuel/Bioproduct Production), heterotrophic algal growth will likely be prohibitively expensive.

Compared to heterotrophic organisms, photosynthetic organisms require substantially more metal ions for growth due to their important role as redox active cofactors in photosynthetic electron transfer (*20*). Among these, iron homeostasis is identified as being critical for optimal growth as it is often a limiting factor under both natural and artificial growth conditions (Nir Keren, *personal communication*). Additionally, many algae are auxotrophic (requiring a particular nutrient or vitamin for growth) for certain vitamins such as vitamin B_{12}, which they must obtain from the environment. The need to include high value compounds in algal media would increase the cost of production considerably. However, algae can obtain vitamin B_{12} by direct association with bacteria, which obtain fixed carbon from the photosynthetic algae in return (*21*). Mixed cultures such as these might reduce the risk of contamination from other adventitious microorganisms. Maximization of productivity will depend on identification of other factors required for optimal growth.

Biofuel/Bioproduct Production

A large number of products can potentially be made from microalgae ranging from fuels to herbicides, and polymers with desirable biophysical or bioactive properties. The ability to genetically engineer microalgae by the addition of genes encoding enzymes of alternative biosynthetic pathways allows for the production of a wide array of chemicals.

Fuels from Microalgae

A number of fuels can be made by microalgae, including fermentation byproducts, long-chain hydrocarbons, and hydrogen. The specific properties of the molecules being produced will dictate the harvesting strategy to be used (see Harvesting and Extraction) and thus the overall energy balance of the process. Methane, ethane, long chain alcohols, oils, fatty acid esters, and isoprenes can all be made using algae. While chemically diverse, they are biosynthetically derived from acetyl-CoA or related small molecule intermediates, with the exception of methane. The following sections discuss in more detail some of these products and their uses.

Ethanol and Other Fermentative Alcohols

Despite its energy density being less than that of gasoline and most biodiesels, ethanol is an attractive transportation fuel because of its use in the existing fuel infrastructure. Ethanol can be blended into gasoline at various concentrations and used in conventional internal combustion engines, which are reported to perform just as well as those with conventional gasoline. At present however, the production of ethanol and other products of fermentation by algae are currently at yields too low to be economically viable. Ongoing research such as strain optimization of species that already produce these molecules seeks to increase the yield of fermentative alcohols.

Research also seeks to divert fermentative metabolism from ethanol production into higher-chain alcohols. These alcohols, such as isobutanol, 1-butanol, 2-methyl-1-butanol, 3-methyl-1-butanol and 2-phenylethanol, have more desirable fuel properties such as higher energy content, and hydrophobicities more similiar to gasoline molecules. These can be mixed with other molecules to lead to a fuel with combustion properties similar to current gasoline (*22*). Simple genetic mechanisms can be used to directly convert ethanol into these other fuels. Though ethanol is a useful biofuel in the near-term, research that moves production to more complex alcohols will undoubtedly prove valuable. Many of these molecules are drop-in or a direct replacement of gasoline and if produced by microalgae, these fuels could in principle be carbon-neutral.

Hydrocarbons and Biodiesel

Another promising route to algal fuel production is the harvest of oils for biodiesel (*16*, *17*). Fatty acids, specifically triacylglycerols (TAGs), can be trans-esterified directly into biodiesel, producing glycerol as the side product. The production of non-polar lipids is in the range of 4-50% of total biomass of various algae strains (*23*). Strains that produce remarkably high levels of these oils are now being studied for other desirable characteristics. One example of productivity achieved to date in Fort Collins, Colorado consists of a 6,000 Liter system that can produce 1.5 kg/day dry weight algae biomass with CO_2 enrichment (Pete Lammers, *personal communication*).

Hydrogen

Hydrogen production from microalgae is achievable now, although at low light-conversion efficiencies and under low irradiation (*24*) but could reach relatively high efficiency values because the hydrogen production process is independent from the carbon metabolic pathways that account for many of the efficiency losses. The maximum theoretical efficiency is 10-13% (*25*). With this in mind, a land area of about 4500 square miles (0.12% of U.S. land area) could effectively supply the transportation fuel demand, with estimated costs as low as $3/kg. The use of hydrogen as a transportation fuel is attractive because it is carbon-free. Its combustion does not produce CO_2 but instead only water.

In green, eukaryotic microalgae, hydrogen production is mediated by the activity of the algal [Fe-Fe] hydrogenase, which catalyzes the reaction in Equation 3:

$$2H^{+}+2e^{-}\rightarrow H_2 \quad (3)$$

There are some major hurdles to algal hydrogen production, however: the enzymes responsible for hydrogen production are sensitive to oxygen, and are not expressed in its presence; ferredoxin, which supplies electrons to drive hydrogen production, is the major electron donor to other cellular redox processes as well; and if large numbers of electrons are diverted to hydrogen production, the pH gradient across the membrane that is established by electron transport from water is not dissipated through ATP production, thus down-regulating the rates of electron transport through the photosynthetic chain (*26*). The isolation of natural strain variants that are better adapted at producing hydrogen has given some insights into methods towards alleviating these problems.

If algal hydrogen production is a realistic route to energy generation, there remain major technological limitations to using hydrogen on a global scale. Hydrogen has lower energy density than ethanol. Additionally, use of hydrogen as an energy carrier for transportation will depend a lot on safe storage and distribution technologies, as refueling stations must be constructed and hydrogen fuel cell technology still needs improvements before it is affordable.

Methods To Overcome Losses in Efficiency

To address the problem of oxygen-sensitive hydrogenases, mutants that produce less intracellular oxygen have been generated. Interestingly, these mutants also show accumulation of more oil than wild-type strains (*27*). Additionally, the oxygen tolerance of hydrogenases varies greatly, according to the amino acid sequence of the enzyme. Biochemical characterization of a variety of algal strains is under way, in order to find hydrogenase homologs that have both high activities and increased oxygen tolerance (*28*). Additionally, a transformation system has been generated that expresses a tagged, active [FeFe] hydrogenase in *E. coli* that allows *in vitro* characterization of hydrogenase isoforms (*29*). Computational studies of various hydrogenases indicate that two gas diffusion channels allow gas diffusion into the reaction center. Therefore, amino acid substitutions that affect the size of the gas channels are of particular interest. The goal is to create a channel that allows free diffusion of hydrogen, but not oxygen (*30*).

Optimization of Production Parameters

Studies in several labs have identified mutants that produce more hydrogen than wild type strains. Kruse and Hankamer have shown that the *stm6* multi-phenotype mutant of *Chlamydomonas reinhardtii* (that cannot transition from linear to cyclic electron transfer) produces H_2 at higher rates and for longer periods of time than its parental strain. Sulfur deprivation, which is known in *Chlamydomonas reinhardtii* to increase hydrogen production, was tested on the *stm6* mutant. Hydrogen production was measured and results indicate the *stm6* strain can produce up to 490% more H_2 over a 300 hour period in sulfur-depleted media when compared to its parental strain, which is not a particularly high H_2-producer.

In an attempt to further boost production, researchers have cloned the HUP1 (hexose uptake protein) hexose symporter from *Chlorella kessleri* into *stm6*, generating the strain known as *Stm6Glc4*. In the presence of 1 mM glucose, H_2 production was seen to increase by 50% compared to the *stm6* strain without the transporter (Figure 12) (*31*). This essentially created a mixed fermentative/ photosynthetic H_2 production system, and conversion efficiency of glucose to hydrogen was near 100%.

Further strain optimization for enhanced light absorption characteristics has been carried out leading to generation of a truncated antennae mutant optimized for a bioreactor with a depth of 10 cm. With this mutant, in high light (700 μE), cell density reached 0.2g/l biomass in less than 5 days. This equates to a 50% improvement in mid-logarithmic growth rate (*32*).

Value Added Products

Value added products from algae have the potential to offset running costs when algae are used as a carbon capture technology. However, market prices and demand will determine the value of products from algae, so the ability to produce a wide array of products and to switch among these quickly may be necessary to microalgae, and its products, economically viable. Advances in genetic engineering and synthetic biology currently underway, will make generation of strains tailored for production of a specific product faster and less expensive.

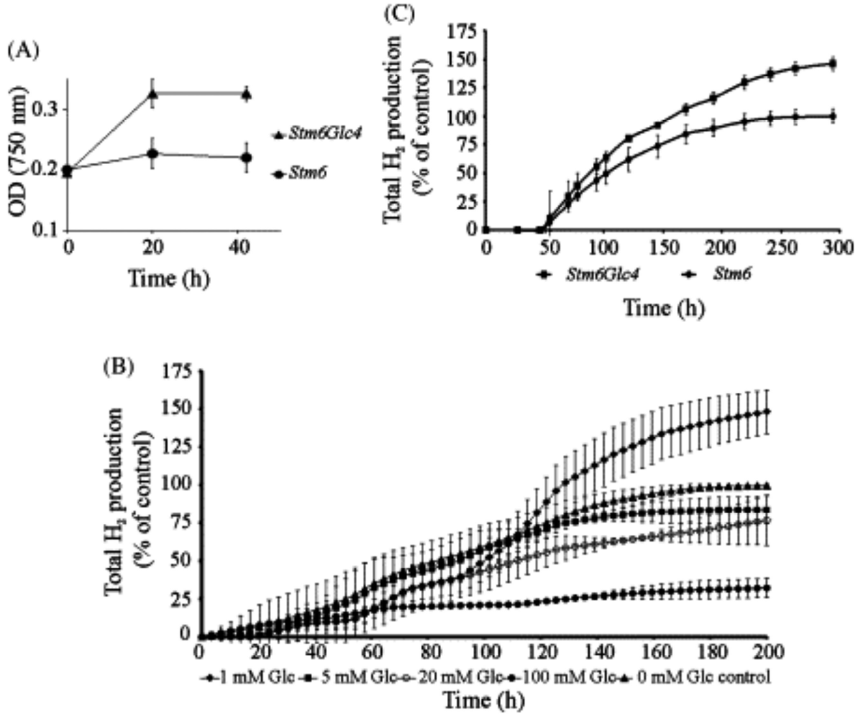

Figure 12. Influence of glucose on heterotrophic cell cultivation and H2 production rates in the glucose transporting Stm6 transformant Stm6Glc4. (A) Replication rates of Stm6 and the transformant Stm6Glc4 in HSM medium (lacks all carbon sources) supplemented with 100 mM glucose. Each data curve represents an average of at least three measurements. Error bars indicate standard error. (B) Total H2 production of Stm6Glc4 as a function of glucose concentration during S-deprivation. Each data curve represents an average of at least three measurements. Error bars indicate standard error. The control measurement (Stm6 Glc4 + 0 mM glucose) was set to 100%. All cell cultures were adjusted to OD750nm = 1.5 (C) Total H_2 production of Stm6Glc4 compared to Stm6 in TAP medium containing 1mM glucose during S-deprivation. Each data curve represents an average of three measurements. Error bars indicate standard error. Reproduced with permission from reference (31). Copyright 2007, Elsevier.

Current Algae Products

Currently, there are four major profitable products from microalgae: Agar, Alginic acid (used as a stabilizer and emulsifier in shampoos etc), Carrageenan (extracted from algal cell wall, used as a stabilizer and emulsifier in foods, and toothpastes), and diatomaceous earth. Microalgae are also a source of pigments that have a number of industrial uses. The carotenoids in particular are additives to food as coloring, vitamin supplements, health food products and livestock feed.

Some studies show the worldwide market value of carotenoids is projected to reach over one billion dollars by the end of the decade (*33*). The market value of one of these pigments, B-carotene, has been projected to reach $253 million by 2009. This pigment is of increasing demand in a variety of market applications including food coloring agent, pro-vitamin A (retinol) in food and feed, as an additive to cosmetics and as a health food product under the antioxidant label. This pigment is conventionally commercially produced from Dunaliella in open ponds (*33*). The market value for omega-3 fatty acids is presently $1.5 billion dollars, with a majority of this product presently extracted from fish oil. This market is expected to grow to over $10 billion in the next several years and with fish stocks rapidly depleting, production directly from algae may become a significant market.

Therapeutic Proteins

Protein-based therapeutics is one of the fastest-growing sectors of drug development (*34*). Microalgae have the potential to provide high yields of specific classes of recombinant proteins more rapidly and at much lower cost than traditional cell culture (*35*). For example, algal chloroplasts have proven to be a good system for the production of antibodies (*36*, *37*), bioactive mammalian protein, and others of pharmaceutical importance (*34*, *38*), and reporter proteins as tools in molecular biology (*36*). Advantages of microalgae over other expression systems would depend on the actual properties desired in the protein produced. Microalgae have proven successful at producing proteins with disulfide bonds, but that lack glycosylation. The time-scale from initial transformation of gene to production of protein of interest in microalgae is a relatively short two months.

Other Products and Services

Some companies are already producing ingredients for cosmetics from algae growing heterotrophically. This means that the microalgae grow in the dark, with no requirement for a light source, making the growth and production much more efficient than microalgae grown in light. However, a feedstock (glucose, acetate, glycerol etc.,) needs to be supplied to the microalgae, in this case and does not allow/involve the direct capture of CO_2 from a fossil fuel source for algal growth.

Many enzymes are required in the production processes of many industries including food, paper and pulp, cellulosic ethanol, etc. Isolation of these enzymes from naturally occurring sources can be time consuming and costly and sometimes requires expensive purification steps where losses of enzyme are encountered. Microalgae could be used as a heterologous expression system for the production of many of these enzymes making a contribution to a diverse array of industries.

Bio-Prospecting

As mentioned previously, the DOE ASP identified 3000 strains of algal species that were interesting from a basic research perspective. Recently, there has been a major push towards similar research identifying strains of microalgae that are well suited for use in industrial processes. The isolation of novel strains that are tolerant to unique conditions present in industrial processes is an effective way to bring down up-front costs when designing a process, as a well-suited organism will allow for major input reduction.

Isolating strains with faster growth rates than strains currently available would improve carbon capture and biomass accumulation abilities without the need for genetic modification. Additionally, isolation and study of strains that grow in hypersaline environments may lead to significant water-use savings. Alternatively, considering alternatives to monocultures might mitigate costs required to prevent or deal with contamination. Finally, finding strains that are well suited to an environment with vast and rapid temperature changes may prove useful for minimizing the amount of heating and cooling necessary to keep a culture alive. In all, the opportunity for bio-prospecting right now is immense, and large-scale efforts have a very good chance of finding strains that are naturally suited for bioenergy production.

Bioreactor Design

The physical location in which microalgae are grown has a dramatic effect on the type of system that is the best for productivity. Typically, there are two competing growth systems for microalgal culture: open ponds and enclosed photobioreactors. The strengths and weaknesses of both have been discussed in great detail in recent years (*39*), and will only briefly be mentioned here.

The major limiting factor to both open pond and enclosed photobioreactor operation is water usage. Typically, sites considered the best for algal production have warm temperatures and high average irradiance throughout the calendar year. In locations with these properties, evaporation from open ponds, and gradual heating of photobioreactors become a problem. The solution to both of these problems is to use more water, either to replace the water lost through evaporation, or to evaporatively cool the photobioreactor. In either situation, total water usage for production processes inflates dramatically, and sometimes reaches the point at which the cost and availability of water renders the process non-viable.

This presents a major opportunity to the scientific community. Major advances in technology for the efficient cultivation of microalgae need to be made before implementation can occur in many regions. Raceway pond design needs to become more resistant to contamination, and resistant to evaporation. Additionally, a low-cost gas delivery technique needs to be designed if algae are to ever capture carbon from power plants. For photobioreactors, major leaps in construction cost and cooling technology must be made before they are price-competitive with ponds.

Harvesting and Extraction

Though algae are very useful for production of high value products through genetic engineering, the harvesting of the desired products can introduce significant costs into the production process. Currently, algae are harvested by centrifugation, which is energetically, very expensive. When producing renewable fuels from algae, up to 50% of the cost comes from harvesting and extraction, and there is a major opportunity for cost savings with innovative harvesting technologies. Improvements in harvesting and extraction technologies will have the biggest effect on renewable fuel prices, as their value per unit volume is relatively low (as compared to other chemicals), and so are profit margins.

Research into harvesting technologies has yielded some interesting insight into the most cost-effective techniques. The biological process of flocculation, in which microalgae clump together and settle out of the media may offer a low-cost method for harvest, as the organisms will self-separate from the media. Flocculation is still poorly understood, however, so current research in that area seeks to understand the molecular factors that trigger flocculation, and identify strains that naturally flocculate.

Another interesting harvesting technique takes advantage of the chemical properties of the chemical being produced. Often, fuel molecules are non-polar, and thus will separate from water on their own. Engineering algae to excrete the molecules or harvesting the molecules while leaving the cell intact would make harvesting trivial, as the molecules will naturally separate from the culture. This process would also make continuous production easier to achieve, as the living cells will continue to produce the desired product instead of being harvested along with the chemical of interest.

The particular harvesting method that will yield the lowest cost will likely be unique to each production process. The fuel produced, algal strain used, and production technique, are the upstream factors that dictate the cheapest harvesting method. As a result, scientists need to develop an array of low cost, energy-efficient harvesting technologies that can be used in for the wide variety of harvesting conditions that will be present in the future.

Water Use Efficiency

Water requirement for large-scale culture of microalgae has been seen as a major hurdle in achieving sustainable deployment of these organisms for biological CCS. However, the possibility of incorporating microalgal growth and carbon capture with current water systems at coal-fired power plants may make water use less of a concern compared to non-integrated algae growth systems. Used mostly for cooling, freshwater use by power plants is only slightly less than irrigation (the largest use of freshwater), at 132 billion gallons per day in the U.S. (*40*).

By coupling microalgal growth to existing water-cooling systems or using strains that grow in brackish or wastewater, freshwater requirements for biological capture of CO_2 emissions from that same plant could be low. A typical 500 MW power plant uses 12 million gallons of fresh water per hour, consumes 250,000 gallons per hour, and often sits near a cooling lake (Figure 13). The impacts on water use at power plants due to the deployment of microalgae can and should be done in a fashion that does not increase usage. However, the use of biocide in cooling water for power plants would likely be incompatible with algae production and so this idea may not be practical in systems other than once-through cooling systems.

Figure 13. The Wisconsin Power and Light Columbia Plant uses vast quantities of water per hour, and circulates that water in a large cooling lake located immediately next to the plant. Locations like this may present an opportunity for low cost retrofitting for algal carbon capture. (Image from Louis J. Maher, Jr., University of Wisconsin)

Integrated Power Plant Design

To capture the carbon given off by coal-fired power plants, existing plants must be retrofitted, and newly designed plants must incorporate carbon capture into the exhaust scrubbing system. The cost of implementing such systems will be the major driving force behind changes, and for algae to be useful, they must be price competitive with non-biological forms of carbon capture (*41*). Furthermore, the type of coal utilized in the plant largely influences the cost of adding biological CCS, as SOx, NOx, and heavy metal concentration vary widely in coal deposits (Adel Sarofim, *personal communication*). The costs associated with CCS will depend on the method of capture and use of advanced separation technologies; whether it is post-combustion or pre-combustion (*3*). Predictions show these costs, in terms of energy penalties, can be approximately 13.5% for separation of CO_2

and another 9% for compression (*2*). Storage costs are small in comparison (*42*). Values in the region of \$52 per tonne/CO_2 for capture and an additional \$10 per tonne CO_2 for transport and storage have been calculated (*43*).

Costs of algae production have been calculated to be \$250 per tonne CO_2 in a photobioreactor system (*16*) and \$55 per tonne CO_2 in a raceway pond system (*44*). However the energy penalty associated with algae as a CCS technology would likely be zero or negative due to the production of large amounts of biomass that can be used as fuel.

De Novo Design

Integrating power plant design with algal carbon capture and remediation could be a means of controlling emissions and capturing SOx, NOx and heavy metals such as mercury (Hg) and perhaps additional contaminants from the flue stream. Currently, depending on the design of the power plant and emissions control measures that are in place, the energy penalty for controlling these emissions is in the region of 1% for NOx, 2% for SOx, and 0.4% for Hg (numbers were calculated from Integrated Environmental Control Software (IECM) assuming a 500-MW power plant burning Appalachian Medium Sulfur coal; SOx scrubbing consists of a wet flue gas desulfurization unit while NOx reduction involves a Selective Catalytic Reduction unit), (*45*). However, at present only 30% of all U.S. power plants have NOx/SOx scrubbing since the costs of implementing this are less attractive than the actual fines. Regulations for Hg emissions are in place in only 19 states and no other trace metals are regulated or scrubbed (*45*).

The results in Figures 14 and 15 show that microalgae can tolerate SO_2 concentrations up to 400 ppm, and NO concentrations up to 100 ppm (which are levels typically found in flue stream from coal-fired power plants) as long as the acidification of the medium in which the microalgae are growing is prevented (*46*, *47*). While studies that establish the pollutant tolerance limits for algae are important, more research is needed to determine the amounts of contaminant actually removed by the algae. If algae were deployed as a CO_2 capture and storage technology, the ability to sequester pollutants would be an added advantage since an additional technology need not be in place.

Perspective on Feasibility, Sustainability, and Impacts

Biofuels produced by microalgae grown on coal-fired power plant flue gases are by definition, not sustainable, since fossil fuels are an unsustainable resource. However, if we consider coal to be a resource available for the next c. 200 years, we can weigh this technology against certain sustainability criteria over this time period. We can also consider this method of carbon capture as a technology that could be applied to coal-fired power plants, natural gas or facilities co-fired with biomass if these were to become adopted at large-scale in the future.

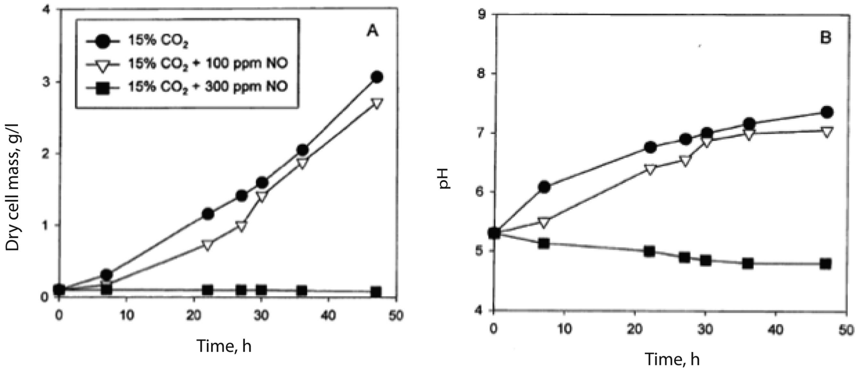

Figure 14. Summary of studies of microalgae growth in simulated flue gas. Productivity of Chlorella sp. KR-1 culture in the presence of NO. Reproduced with permission from reference (45). Copyright 2002 Elsevier.

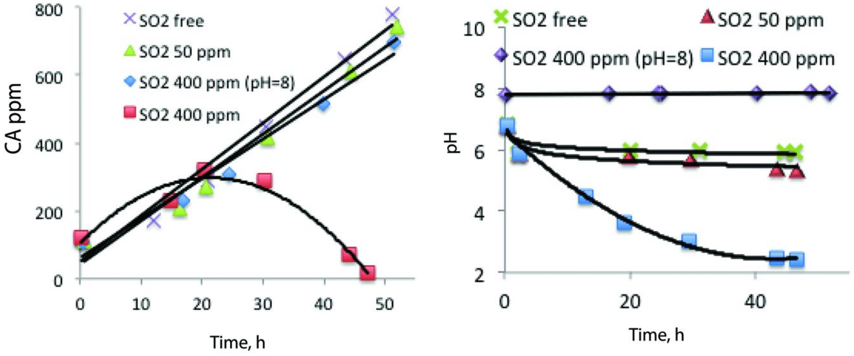

Figure 15. Productivity of Nannochloropsis salina culture in the presence of SO_2. Results indicate that productivity is not significantly affected by NO and SO_2, at similar concentration levels to that of combustion flue gas, as long as pH is maintained in a favorable range. Redrawn from data from reference (46).

Based on information available from existing technology, land and water are major resources needed to realize carbon capture by algae at power plants (*7*). Estimates of land use vary depending on the productivity of algae and whether grown in ponds or photobioreactors. Numbers for water use also vary between these two approaches as pond systems have associated evaporative losses but have the ability to use salt, brackish or wastewater depending on the strain of algae grown. Some working photobioreactors systems employ water reuse/recycling, which helps to lower total water use. Considering the higher reported productivities that can be achieved in photobioreactors compared to those for existing pond systems, there is a trade-off between the capital costs and the apparent benefits and drawbacks of these systems at present.

Siting Issues

The number of suitable sites for deployment of a biological capture technology as described in this review is uncertain as the requirements for land area, type of land, and type and capacity of water resource depend very much on the needs of the algae system employed. Siting close to the CO_2 source may have its benefits in terms of allowing integrated design and synergy between waste heat and water use of the power plant but the downside is that sufficient land with the desired characteristics may not be available.

Suitable land for raceway pond systems has been suggested to have a slope of no more than 2% for construction costs and water lifting and to have a high clay content to minimize water percolation (*48*). Although the characteristics of surrounding land is important, it need not be restrictive since other options exist such as siting elsewhere with access to a CO_2 pipeline and water source or the use of reactor systems.

Importantly, the effects of land use under any of these scenarios on existing carbon sinks, soil quality and biodiversity must be considered to determine sustainability and impacts on green house gas (GHG) emissions.

Impacts on Local Population

The implementation of algae as a technology to capture and utilize carbon has the potential to have both positive and negative impacts on sites where deployed and on the people living close to those sites.

Benefits for local populations could include improved ground water, lower local emissions of carbon, SOx, NOx, and heavy metals such as mercury. A new industry around carbon capture and production of liquid transportation fuels by algae could have the potential to provide local jobs, improve local economy, improve local prosperity, and benefit the social well being of the local population and employees. However, competition with existing local business activities would need to be considered if such a business is to be sustainable and especially if algae were to provide a diversity of high-value products.

Negative impacts on the local population include the risk of contamination of waterways, the possibility of algae blooms and suffocation of other species (plant and animal), and competition for water use.

Research can help to minimize these risks as nutrient dependant strains of algae (where algae cannot grow unless supplied with a particular nutrient/chemical) can be found or engineered (*21*). Re-use, treatment, recycling and monitoring of water could minimize total water requirements and the risk of release of contaminants to the surrounding environment. Examples of successful containment due to the growth requirements of algae exist in the San Francisco Bay Area where side-by-side algal salt ponds show no/little apparent cross-contamination between ponds, probably due to differences in their pH and salinity tolerance. The risk of potential negative impacts could be minimized with the right engineering, science and management practices.

Global Impacts

As discussed previously the amount of oil produced by algae varies with strain and growing conditions. Calculations based on reported production from some algae facilities suggests that the contribution from one year's production would meet less than a 1000th of the current U.S. daily demand of barrels of oil. This highlights the need for game-changing research to improve productivity, but even with these improvements production of oil from algae would make only a small contribution to offset U.S. oil use.

Targeted application of the energy dense fuels from algae, for example for aviation, seems more realistic and practical than attempting to displace liquid fuel use for the whole transportation sector. A major strength of algae, compared to other bioenergy technologies, is its ability to produce energy dense oils, which can be turned easily into diesel type fuels. This would perhaps be the most appropriate target of an algal oil production system since other non-fossil sources of this fuel are limited. Other oil producing sources, such as oil palm, and bacterial and yeast systems look promising (*49*), but scalability and sustainability issues associated with these have yet to be solved. The use of algae compared to these other methods for the production of energy dense liquid fuels should be assessed to determine the most sustainable, efficient and low-cost option.

Need for Systems Analysis

The need for thorough systems analyses on coupling algae growth to CO_2 emissions from power plants to determine the real effects on GHG emissions, and other sustainability criteria is apparent. The amount of fossil fuels that would need to be displaced in addition to the required amount of carbon to be captured by growing the algae to make a substantial reduction in GHG emissions should be determined.

These tasks require developing definitive costs for the various unit processes from producing algal biomass to producing algae oil in the context of land, water needs, and the proximity of a CO_2 source. This would be a complex undertaking, but necessary for assessing the potential of algal technology to contribute to GHG reductions and our energy needs.

Summary and Conclusions

For algae to be deployed as a carbon capture technology and contributor to energy supply the process must be able to compete on a cost basis with other energy related technologies for carbon capture, production of fuels and other services. To be sustainable and deployed on a global scale the amount of water, energy, and land used must also be minimized to help preserve our natural ecosystems and avoid competition over these resources with other uses.

Competing technologies include non-biological carbon capture and storage (CCS) of CO_2 from fossil fuel sources, hydrogen production from fossil fuels and biomass, and production of hydrocarbon fuel molecules by micro-organisms (bacteria or yeast) using sugars derived from biomass feedstocks such as corn, sugarcane and lignocellulosic biomass. Currently, CCS technologies are energy intensive and expensive, often requiring specific operating conditions of temperature, pressure, pH, and concentration in addition to specific citing where the properties of the subsurface allows CO_2 storage. Worldwide there are several carbon storage projects underway (*50*), but in sum, these projects, including CO_2 injected into oil reserves for enhanced oil recovery, represent only megatons of CO_2 that has been diverted from the atmosphere. It is a seemingly low volume in comparison to the quantities necessary to make a significant impact and indicates the need for additional CCS alternatives.

Algae could be an alternative or additional technology to this if the overall running costs are less and implementation at scale can be achieved. Considerations such as land availability, and water use may limit the potential for the sustainable deployment of algae as a means of capturing carbon from fossil fuel sources globally and these limits need to be assessed by systems analysis. Systems analysis could also help to assess the progress towards minimizing these needs if some of the key technological advances, as identified by the workshop and discussed in this chapter, are achieved.

Improvements to the rate of carbon capture and fixation by algae can be made by targeting many aspects of algal photosynthesis. Alterations to the light harvesting part of photosynthesis by decreasing light saturation; increasing light capture; and increasing wavelength of light utilized; can all lead to an increase in photosynthetic efficiency. In addition, exploring opportunities in engineering for coupling water use and low-grade heat from power plants to algal growth, complemented with the bio remediation capabilities of algae could further improve sustainability, and lower costs of deployment of algae as a carbon capture technology.

Economics are a key aspect to making algae a viable option for contribution to our energy supply and as a production system for high value products. Technological advances that bring harvesting and extraction costs down, and ultimately finding or engineering organisms that show an order of magnitude increase in efficiency will all impact the extent of deployment of this technology and its successful competition with other carbon capture and liquid fuel production technologies. The production of value added products could potentially offset running costs; however sustaining this with respect to the demands of the market place may be difficult. Having the ability to switch production from one commodity to another on a day to day basis may be important to avoid flooding the markets with a particular product. The goal of achieving carbon capture and production of fuels or high value products at low cost of materials and high efficiency should be the primary goal and the realization of technologies to achieve this should be the focus of fundamental research.

The major findings suggest that focusing research on one area alone will not lead to the necessary improvements but that research focused on a few key aspects of algae biology provides opportunities for increases in efficiency that together would lead to an order of magnitude improvement in the operating photosynthetic efficiency.

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Chapter 8

Unintended Consequences: Evaluation of the Pros and Cons of New Technologies and Regulatory Drivers as They Relate to the Potential Changes in Behavior and Infrastructure

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The development of new technologies is generally exciting and offers a number of benefits to society and users. However, as these technologies are developed there is a bias towards the positive impacts and very little consideration to the potential negatives or thought toward what may be some of the unintended consequences. By focusing on a few case studies, this chapter will consider the unintended cosequences of societal choices, governmental regulations, diversion of resources, and ultimately the ethical implications of technological trends and potential solutions to the energy issue.

Scientist, engineers, and entrepreneurs are generally on a quest to make the world around us better in some fashion. These individuals have an overall drive to improve lives. These improvements may be through the development of new medicines, new materials, new products, or new processes. It appears that there is a quest is to live longer, be healthier, be more efficient, and to enjoy technologies.

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

During the last one-hundred years, there have been dramatic changes in technologies. In the late 1800's, the primary modes of transportation were powered with steam, human, or animal power. Traveling long distances required significant planning and time. Electricity moved from a scientific and laboratory curiosity to wide spread applications in homes and industry. Consider the improvements in communication, from the telegraph to the telephone, to internet conference calls complete with video transmissions.

Things that are common place today were the stuff of science fiction during the life of Jules Verne. Yet, do we really listen to those science fiction writers? The writers of science fiction really have and still do play a key role in the development of technology. They not only explore the what if's, like can man fly from place to place or be "teleported" using a transporter like the one used in *Star Trek*, but they also explore the potential consequences of that technology.

Exploring the consequences of technology is not a new concept. King Midas of Cretan folk lore wanted and was granted the ability to turn "all he touched" into gold. Yet, he soon discovered that this ability was all encompassing. His food and his daughter turned to gold. This was certainly not his intention nor was it a consequence that he had foreseen. If he had, would he have pursued this desire?

These themes or cautionary tales are very evident in literature, science, and politics. Take these four quotes:

- While we are free to choose our actions, we are not free to choose the consequences of our actions. – *Stephen Covey*
- Nobody ever did, or ever will escape the consequences of his choices. – *Alfred A. Montapert*
- In nature there are neither rewards nor punishments; there are consequences. – Robert Green Ingersoll
- Consequences are unpitying. – George Eliot

Yet, as science and technology advance, do we listen to these cautionary statements? When the scientist is at the bench, or the engineer is developing the next breakthrough, is the question ever asked, "Just because it can be done, should it be done?" Are the consequences ever explored upfront, before the preverbal genie is released from the lamp?

In order to further explore the impacts of technology and the potential consequences, the examination of a few case studies can be beneficial. These case studies highlight a number of concepts that need to be considered when evaluating the potential consequences. The case studies highlight the types of questions that need to be addressed as new technologies or solutions are developed. This chapter will start with the impacts of social changes, i.e. the industrialization of agriculture, a review the precautionary principal, and move to using chemicals to solve specific problems. After examining these particular cases, one is better prepared to examine the challenges that may be presented as our society looks for alternatives to petroleum based fuels, e.g. biofuels.

The Industrialization of Agriculture

Historically, agriculture was community based, dependent upon the local environment, and variety was limited. In order to improve yields and varieties, humans have been conducting genetic engineering experiments and making genetic modifications. These initial experiments were performed from a more traditional natural selection view point, selecting specific animals for their milk, meat, wool, usefulness, and the ability to thrive in a given environment. Similarly, crop plants were also selected this way and developed to meet specific criteria.

As our society changed, so did agriculture. Today, a person can go to the grocery store and find a large variety of fruits and vegetables regardless of time of year. Thus, the factors impacting the selection of the various plants and animals have changed to meet perceived needs. Focusing strictly on crops, plants are chosen or developed to meet an expanded variety of properties: ease of production, resistance to disease, resistance to flood or drought, and resistance insects. Additionally, you can add shelf life, specific nutrients, and ability to ship for miles via truck, trains and cargo vessels. All of these seem like wonderful improvements (*1*). Yet, has anything been lost?

Most of us have made the observation that fruits and vegetables in a typical supermarket don't taste quite as good as the similar one from your own garden. Tomatoes are prime examples. They look pretty in the store, but may taste watery or have no flavor. They may look right on the outside but are green or lack the vibrant colors on the inside. So, is the tomato at the store better?

This, of course, is a value judgment (*2*). And, this judgment is highly subjective and dependent upon the specific needs of the person or persons doing the assessment. For the grower, the ability of that tomato to go from a seed to something that can be sold is highly important. So the grower is looking for a plant that can grow in the specific climate where they are located. Other considerations are the size of the tomato, its appearance, and maybe the time from planting to maturity. For the shipper, the ability for the product not to be damaged in shipping and shelf life are key. For the grocer, the appearance of the tomato, as well as not spoiling, are considerations. For the purchaser, the appearance and the availability result in the sale. Was taste a top priority in this listing?

So, what has been given up? Taste is one thing. But, there are others as well. When you go to the garden store to purchase your tomato plant or seeds for the garden, how many varieties are there? Certainly more than you see in the local grocery store. How many colors are available? They typically range from purples, to burgundy, to yellow. And, unless you are going to a specialty store or a farmers market you are not likely to see these color variations. And have you ever tried to grow a tomato from seeds from a store bought tomato? Many of them are hybrids and will not reproduce from the seed so you can't grow them.

Society has chosen certain characteristics over others – ease of shipping, uniform shape, uniform color, availability, the ability to patent, time to maturity, resistance to climate, resistance to pests, and resistance to disease all at the expense of flavor and genetic diversity. Thus, society has made a significant value judgment. But, is it the right one?

This similar scenario has been played out with multiple crops: rice, wheat, oats, peas, beans, etc. It has also been played out in animal husbandry: Holsteins for milk, Angus for beef, Angora for wool, etc. In fact there is such a concern for the lack of genetic diversity; that now there is an "heirloom" resurgence in animals and in plants. There is a growing trend and a school of thought that the value judgment may or may not have been correct. Or, at least a recognition that there may be a significant consequence if these "heirloom" varieties disappear. These are value judgments that continue to be expressed as research in other areas continues and as one solution over another is chosen.

The Precautionary Principal

Even though we are surrounded by cautionary tales and have heard these tales since childhood, do we really listen? Or, do we fool ourselves into believing that the benefits outweigh the consequences? Albert Schweitzer once said "Man has lost the capacity to foresee and forestall …. He will end up destroying the earth." Examples are all around us indicating that this may very well be the case. Tuberculosis is returning and this one is drug resistant. Many infections cannot be treated by antibiotics because of the overuse or misuse. Immune systems are not as resilient due to the abundant use of antimicrobials. In many of these cases, it is too much of a good thing.

So what has been lost? What have we chosen to ignore? Have we deceived ourselves? The precautionary principal is a voice of these nagging thoughts. The maxim "primum nil nocere" or "first do no harm" has been around for centuries. It was originally attributed to Hippocrates and is part of the Hippocratic Oath. Yet, this has been violated many times by well-meaning physicians and their charges (the overuse or misuse of antibiotics as an example). Why? It certainly wasn't intentional. It was a lack of understanding and long range foresight, and maybe a little of a compounding effect.

The precautionary principal is at the heart of this discussion (*3*). In 1972, the United Nations Conference on Environment and Development issued a statement outlining this principal. It is known as the 1972 Rio Declaration precautionary principal:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

The date of this Declaration is particularly significant. The environmental movement was in full swing. Rachel Carson's book "Silent Spring" had been published a decade earlier. Richard Nixon founded the Environmental Protection Agency (EPA) and it began operation in December of 1970 just two years before. The Resource Conservation and Recovery Act (RCRA) would be implemented beginning in 1976. And the late 1970's and early 1980's would highlight the consequences of past actions, high profile examples being “Love Canal (*4*) and Times Beach (*5*).

Individuals were beginning to understand that there were significant environmental consequences to their actions. There was no malice behind the actions that led to the consequences. There were only good intentions. Hence, there is a better understanding of what the potential negative consequences are or may be. Researchers need to consider and reflect upon these consequences as solutions are developed and implemented.

The DDT Story

The mention of Rachel Carson typically brings to mind the DDT (dichlorodiphenyltrichloroethane) Story (*6*). This is truly a story of two generations. One generation saw the development and use of DDT as a wonderful achievement and a huge success, while the next generation saw it as an ultimate environmental tragedy. The truth or reality is probably something in between.

When DDT was developed and put into “routine” use in the late 1940’s and 1950’s, it was seen as powerful insecticide with many positives. It helped prevent insect damage to crops thereby allowing more food to be produced. It was highly effective against mosquitoes, lice and fleas and is generally credited with helping to reduce malaria (*7*), typhus, yellow fever and the plague in many areas (*8*). Thus, it was seen as a huge positive by many, particularly in poor marshy areas of the world. How could this stuff be bad?

The consequences did not present themselves immediately. It took time. Whether or not “too much of a good thing” played into the scenarios is not certain. But what is certain, is that bioaccumulation effects became evident. This resulted in a depletion of birds due to the thinning of egg shells. The Bald Eagle became the symbol of everything that was wrong with DDT. Cancers in humans were discovered and linked to DDT. None of these consequences were anticipated.

Similar stories abounded in the 1960’s and 1970’s. Tetraethyl lead a common ingredient in gasoline, gave rise to higher lead levels in cities and resulted in human health issues. Dioxins, polychlorinated biphenyls, and asbestos were all wonder products that ultimately received a very bad reputation.

The Toxic Substance Control Act

The recognition that some materials, while they had wonderful properties may have significant negative impacts led to the implementation of the Toxic Substance Control Act (TSCA or Act) in 1976. The Act was and is intended to regulate the introduction of new or already existing chemical substances in commerce in the United States. The Act provided the EPA with the authority to address and assess chemical substances whether manufactured or imported for potential risks, exposures of concern, uses, distribution and disposal prior to introducing these chemicals into commerce (*9*).

This Act was far reaching and well ahead of its time. Its overall intent was and still is directly related to the precautionary principal and has been subsequently modeled by other governments. The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is the European Union's version. The REACH regulation was not adopted until December 18, 2006 (*10*). These regulations provide a framework for asking some of the tough questions prior to placing a chemical into commerce. However, as highlighted in the next case study, the regulatory framework is not a panacea. The regulations only address certain issues, and do not necessarily foresee political and social ones. Additionally, the regulation itself may become a significant barrier to positive solutions due to economic considerations, time to work through the permitting or testing, and the conflicting goals or agendas.

The MTBE Story

Tetraethyl lead was a common ingredient in gasoline. With the discovery that this additive resulted in higher airborne lead contamination, its use was phased out in 1979. The tetraethyl lead additive was used primarily as an anti-knock or octane booster in gasoline. With the phase out, another way of boosting the octane needed to be found.

Also at the time of the tetraethyl lead phase out, "smog" in the summer and carbon monoxide in the winter were significant air pollution problems (*11*). The primary source of smog and carbon monoxide came from vehicle emissions resulting from the incomplete combustion of gasolines and diesels. Smog results from a mixture of volatile organic compounds, nitrogen oxides, and sulfur oxides resulting in the development of ground level ozone when combined with sunlight. The word smog is not typically in use any more and what were once high smog days are now usually referred to as "ozone alert" days.

So, the gasoline producers were faced with two problems: a reduction in the octane, and a need to minimize the emissions from the use of their product. As this was a political issue as well as a scientific one, there was political pressure to mandate a solution. Oxygenates were one solution to this complex problem and methyl tert-butyl ether (MTBE) was a likely candidate. MTBE had good octane boosting properties as well as the ability to support a more complete combustion (*12*). In order to reduce air pollutants, the use of oxygenates in fuels became more important. MTBE became the oxygenate of choice in many areas. In some cases, the use of MTBE was mandated. Thus, MTBE became widely used in several states including California and Colorado. Then the unintended consequence appeared.

The physical and chemical properties of MTBE allowed the material to easily migrate and pollute large quantities of groundwater if released into the environment. In the early 1990's, evidence of this groundwater pollution started appearing in drinking water wells in California and Colorado. This resulted in massive cleanup efforts which are still going on today. The seemingly ideal, and in some cases mandated, solution to one problem created another potentially more serious one.

Thus, it is evident that some characteristics or criteria may be beneficial but other characteristics may be harmful. Additionally, the pros and cons of a particular substance or solution may vary by vantage point or need. Taking thes case studies and applying them to the implementation of new technology may be very helpful in assessing particular consequences or negative aspects of the introduction of a new technology.

The Challenges of Biofuels

There are a number of potential challenges that are faced with the introduction of biofuels. Some of these are scientific and technological, while others are political and societal in nature. The Department of Energy (DOE) has stated that biofuels are part of the next set of grand challenges for development as a means of minimizing the reliance on fossil fuels. Recall that there are three significant challenges related to the use of fossil fuels:

1) The supply of fossil fuels is finite
2) The current demand for fossil fuels in the United States is greater than the domestic production
3) The supply of fossil fuels used by the United States comes from sources out of the control of the United States

Hence, there is a need to be proactive in the development of alternative fuel sources, particularly fuel sources that allow personal mobility, i.e. a replacement for gasoline and diesels. Biofuels are one potential solution to this problem.

The DOE has put forth to the scientific community the following challenges in an effort to address perceived needs:

- Development of the next generation bioenergy crop
- Discovery and design of enzymes and microbes with novel biomass-degrading capabilities
- Development of transformational microbe-mediated strategies for biofuel production

Yet, there is no particular discussion of the potential implications of these challenges other than the replacement of gasoline and diesel. In fact many of the impact statements are like this one from the DOE Report on Bioenergy Research Centers: A Overview of the Science (*13*):

> Certain fungi and bacteria specialize in producing enzymes that degrade biological materials in natural environments. Discovering, harnessing, and enhancing the best biomass-degrading enzymes and microbes in nature ultimately will have a significant impact on increasing the efficiency and reducing the cost of cellulosic biofuel production.

The focus is on the benefits of the proposed technology with very little articulation of the potential negatives or unintended impacts. What might these potential negatives be? Are there any significantly adverse impacts that should prevent a researcher from pursuing these solutions?

To understand the potential implications, the challenges that biofuels present need to be understood. First, what is the source of the biomass that will be used to generate the fuel? Then, what process or processes maybe used to take the biomass to a fuel? These may include cellulose hydrolysis using enzymes, production of specialized algae, or fermentation by microbes. Finally, there are the separations and processing technologies that will be needed to take the resulting fuel be it methane, ethanol, an ester, or an oil derived product from the process to the point source where the fuel will be used.

From a consequence discussion, the impact of the final processing, shipping and use is likely to result in fewer unintended consequences than the source of the biomass and conversion of the biomass to a fuel. This is because society has dealt with many of these previously. However, there are likely to be some consequences resulting from the change of a gasoline/diesel infrastructure to a biofuel infrastructure. This will likely result in changes in vehicle technology as well as economic shifts. For simplicity, the focus here will be on the source of the biomass and conversion stages of the process.

The Source of the Biomass

As it stands now, the primary sources of biomass for the production of fuel are sugar cane and corn for the production of ethanol. There are several other potential sources under investigation which include oil bearing seed crops, stovers, switch grass, waste materials, etc. Additionally, algae are a potential source of biomass. Regardless of which source of biomass is used there are two common factors – space and access to water. Where is the biomass going to be produced and how is that space currently utilized?

Depending upon the source of the biomass to be utilized, the criteria for the appropriate space will be slightly different. For example: the land and water use requirements for corn are significantly different from that for switch grass. Additionally, depending upon the algae chosen, they can be grown in vats or on thin films. The needs of the biomass are going to have to be considered as well as the potential quantities of the biomass needed to develop the fuel.

Corn is an excellent model for further discussion. In order to grow corn, the plant needs nutrients and water – thus the soils must be correct for proper corn production. Additionally, weather conditions do not allow for corn production on the same plot of land all year. Thus, there will be times when the plot of land is not producing for this application. The grower or land user will have to make some initial value judgments:

- Is corn the best use for this piece of land?
- To prepare this plot, what are the costs in water, fertilizer, etc.?
- What is the potential return from the corn for a fuel application versus other uses?

Corn is not used strictly in a fuel application. Corn is a primary grain for human and animal consumption. Any corn produced for a fuel application is potentially diverted from a food application. This is a similar quandary for many of the potential sources of biofuels. Thus, a value judgment between food and fuel will have to be made.

Several value judgments and trade-offs are going to have to be managed just to produce the source of the biomass. Here is a listing of some of the considerations:

Land Use

- Amount of land required
- Diversion from one land use to another (food, housing, biodiversity or fuel)
- Nutrient requirements

Water Use

- Water source
- Water amounts
- Diversion of water from consumption, industrial, or environmental applications

Crop Use

- Food source for human consumption
- Animal feeds
- Impact on soils

Conversion of the Biomass

Once the tradeoffs have been made, it is likely that there will be multiple sources of biomass used to produce the end product. For some biomass sources, the conversions may be simpler than others. This is certainly the example of the corn and sugar cane. The reason that these two sources are in use is that the technology to produce ethanol from these sources is widely known and the microbes in use have been present for quite some time. However, for other sources such switch grasses or some of the other seed crops, the microbes and enzymes in use are not as efficient as they need to be to be economically viable or may have yet to be identified. Similarly, the preferred algae may have not yet been identified. The identification of these organisms has been stated as one of the grand challenges.

However, in terms of consequences look closer at the DOE wording:

> Discovering, harnessing, and enhancing the best biomass-degrading enzymes and microbes in nature ultimately will have a significant impact on increasing the efficiency and reducing the cost of cellulosic biofuel production.

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

This grand challenge does not stop at the identification. There is an implication of creation in the wording. With the newer technology and genetic engineering that is already taking place, the possibility of creating the appropriate organism to employ in this conversion is not unforeseeable. This is no longer in the realm of science fiction. Scientists and engineers are already tweaking and patenting microbes to do specific tasks. So, what are the consequences?

The positive consequences can be predicted as the hope is to increase efficiency, allow for the use of alternative biomasses, produce higher yields, etc. But, what about the negative consequences? What happens to the microbes that don't work? Are these potentially harmful? Are there potentially hazardous byproducts produced? What will become of the wastes? Can the wastes even be used? The list of questions generated can go on. But the fundamental question still remains, "Just because we can − should we?"

Other Implications

As previously stated, consequences of these challenges are not just scientific. There are political consequences. There are regulatory impacts via mandates and current restrictions. Are some of the better pathways to solving the problem being blocked because of the current regulatory environment? For example, TSCA requires significant testing prior to producing a material for commercial use; does the cost of this test impact which solutions are put forward? Of course, it does. This has already happened in the areas of biodiesel versus renewable diesels.

Additionally, are certain pathways favored over others? Of course, this is evident in the current regulatory environment associated with the production of ethanol using corn. Subsidies and quotas are in place to enhance the production of corn for fuel use. What have been the consequences?

- Diversion of land from wheat or other crops to corn even though the land may be better suited for the other crop
- Diversion from grazing land to crop land
- Diversion of corn from the food or feed market to the fuel market increasing costs of other products such as pork, beef, and milk

All regulations and subsidies have impacts, and it is usually not clear what the overall impact will be and whether the ultimate impact is viewed as a positive one. The implications and impacts must be balanced.

Our Challenge and What Next

In addition to the scientific questions and impacts, regulations can cause huge societal consequences. The challenge that is faced with the biofuels includes both types of implications. From a regulatory side, there are some strong positives including the resources to investigate the challenges. However, there are some significant barriers and potentially harmful outcomes if the regulations are too far ahead of the science as was the case with MTBE. Regulations tend to be reactionary and currently are not adequate for some of the technologies being explored. Thus, it is up to investigators to ask some serious questions and recognize some of the potential outcomes whether positive or negative.

Those in this area of discovery need to be characterizing the potential threats and possible problems with the technologies being developed. There is never an ideal solution, only solutions which balance multiple needs better than others. The potential negatives need to be clearly articulated and what is known about the negatives discussed.

The problem needs to be re-framed and looked at from other points of view. How would this solution impact different stake holders? Ask the what if questions.

Alternatives must be assessed. Might there be a different pathway to get the same or better result? If one path is chosen, what pathways are eliminated? What are the criteria that need to be balanced? What are the resources required and what are the alternative uses of a resource? Courses of action must be discussed but with knowledgeable people. React with caution and monitor the implications. Finally, ask the question about what could go wrong? And, be honest about the answer.

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Chapter 9

Economist's Perspective on Biofuels

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Economics is a discipline that aims to analyze resource allocation by individuals and societies. It investigates allocation choices by individuals, which may include purchases, employment, life decisions, as well as resource allocations by firms and governments. It also aims to explain and evaluate outcomes of markets and selection of policies. Economists distinguish between choices that are optimal from the perspective of individual agents and choices that are optimal from a social perspective. They suggest policies that will induce private choices to coincide with social optimum. However, economists do not run the world and actual policy choices are typically different from what economists prescribe. Often then, the economist is charged with the task of assessing the impact of actual policies and proposing ways to improve them. Although tools of the trade are used to analyze the economics of biofuel, the body of information and the subsequent conclusions that are arrived at are often as diverse. We will use the basic tools of supply and demand to understand how biofuels fit within a stylized market for energy, and explore how climate change considerations may affect biofuel utilization. Then, we expand our analysis to deal with the impact of biofuel on food and fuel choices, followed by an analysis of actual biofuel policies while

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taking into account political economy considerations as well as uncertainty and enforcement issues. Finally, we provide an overview of results of some quantitative studies that predict the outcomes of introducing biofuels and assess their future.

Keywords: Biofuels; Biomass; Fossil fuel; Food; Policy; Adoption

Introduction

Economics is a discipline that aims to analyze resource allocation by individuals and societies. It investigates allocation choices by individuals, which may include purchases, employment, life decisions, as well as resource allocations by firms and governments. It also aims to explain and evaluate outcomes of markets and selection of policies. Economists distinguish between choices that are optimal from the perspective of individual agents and choices that are optimal from a social perspective. They suggest policies that will induce private choices to coincide with social optimum. However, economists do not run the world and actual policy choices are typically different from what economists prescribe. Often then, the economist is charged with the task of assessing the impact of actual policies and proposing ways to improve them. Tools of the trade are needed to analyze the economics of biofuel, but the body of information and the subsequent conclusions that are arrived at are often as diverse.

First we will use the basic tools of supply and demand to understand how biofuels fit within a stylized market for energy, and explore how climate change considerations may affect biofuel utilization. Then, we expand our analysis to deal with the impact of biofuel on food and fuel choices, followed by an analysis of actual biofuel policies while taking into account political economy considerations as well as uncertainty and enforcement issues. Finally, we provide an overview of results of some quantitative studies that predict the outcomes of introducing biofuels and assess their future.

Biofuel and the Market for Fuel

It is a reasonable starting point to consider the market for biofuel as a derivative of the market for liquid fuel and see how biofuel fits within the demand and supply forces of liquid fuel markets. Our analysis will be stylized to illustrate basic principles. We will begin the analysis by assuming competitive behavior but later on we will see how the analysis changes when we consider oil cartels, such as OPEC.

The demand for biofuel is derived from the demand for liquid fuels. Liquid fuels are the most efficient means to provide energy to the current vehicular infrastructure and thus the demand for liquid fuels are derived from demand for vehicles. The demand curve denotes the amount of fuel that consumers are willing to pay at a given price. If we assume that consumers as a whole gained benefits measured in monetary terms from the consumption of fuels, then the demand at a given quantity is the incremental benefit from increased quantity of fuel. It is reasonable to assume that the quantity demanded of fuel declines with the price of fuel. The demand for fuel is also dependent on income and it is reasonable to assume that demand increases with income of consumers, thus a reasonable conclusion is that the drastic economic growth over the last thirty years in Asia has been the main source of growth in demand for fuel.

Assume a commodity called 'fuel' that can be produced from fossil fuels or biofuels (even though in reality consumer may treat the two somewhat differently). Biofuels encompasses a broad range of energy carriers, some liquid and some gaseous. Some biofuels have the same energy content as their fossil-derived analog, and some biofuels are chemically identical to their fossil version. Others such as ethanol from corn and sugarcane, namely, bio-ethanol, contain less energy than their fossil counterpart. For simplicity and unless stated differently, define one unit of biofuel to contain the equivalent amount of energy as one unit of fossil fuel. Figure 1 depicts the demand for fuel in two periods: Period 0, which corresponds to 2000, and Period 1, which corresponds to 2010. The increased economic growth between these two periods account for the upward shift in demand.

A supply curve denotes the amount of output, in this case fuel, producers are willing to provide at a given price. Production of output, like fuel, is costly and the supply at every level of production is equal to the incremental cost associated with the production of the marginal unit. In Figure 1, we have two supply curves. The supply of fossil fuel that presents how much fossil fuel will be supplied at a given price. It is increasing with the price of fossil fuel reflecting that as the price of fossil fuels increases more will become available. At very high prices, fossil fuel supplies includes fuels produced from tar sands as well as fuels that may be converted from coal. We also have another supply curve that has a joint supply curve from fossil fuel and biofuel. This joint supply curve consists of the supply for fossil fuel below a certain price because biofuel will not be available before a minimal price P_A. P_A and Q_A also denote the equilibrium price and quantity of Period$_0$. And in the initial period, only fossil fuel was produced. If biofuel would not be introduced, then the equilibrium point would have been point B and the price of fuel will P_B and quantity of fuel will be Q_B. However with the introduction of biofuels, the price of fuel will become P_C and the quantity will become Q_C. The introduction of biofuel reduces the price of fuel and increases the quantity of overall fuel consumed. However, the quantity of fossil fuel consumed declines from Q_B to Q_D and the difference between Q_C and Q_D is the amount of biofuel consumed at the higher price. *Thus, sufficiently high demand will lead to the introduction of biofuel and once biofuels are introduced, they tend to reduce the price of fuel compared to what it would have been otherwise.*

One of the major reasons economists are concerned with fossil fuel is because of the externalities they generate. The externalities are the negative side effects of burning of fossil fuel that is not intended by the producer or consumer of fossil fuel but harmful to society and the environment nevertheless. There are several types of externalities associated with fossil fuel. The most notable is greenhouse gas emission that is a global public 'bad' because it affects humanity regardless of where it originates. Another major externality is local air pollution, contributing to smog and other air quality problems associated with emission of gasoline and diesel. There are also externalities associated with driving, for example congestion. There is a social cost for each of these externalities, and it can be monetized (in principle, but it is not an easy task). We will assume, as much of the literature does, that the externality costs of fossil fuel are greater than those of biofuel. The reason is that biofuels are renewable which sequester greenhouse gas emissions (however, their production and processing emits greenhouse gases). In an idealized world, consumers pay for the externality costs in addition to the private costs of fuel production and that increases the cost of providing fuel. In Figure 2 we add two curves: the supply of fossil fuel including the externality cost and the supply of fossil + biofuel with the externality cost. The first curve is also the marginal social cost of fossil fuel and the second is the marginal social cost of both fuels. These supply curves represent the incremental social cost of producing given fuel quantity. The term social cost refers to the sum of private cost and externality cost, and the two curves represent incremental social costs. The social optimum is where the demand curve intersects with the supply curve that is based on the social cost, namely at Point E. The price of fuel that represents the sum of the externality and private cost is equal to P_E. The quantity of fuel produced is equal to Q_E. The quantity of biofuel produced is $Q_E - Q_A$.

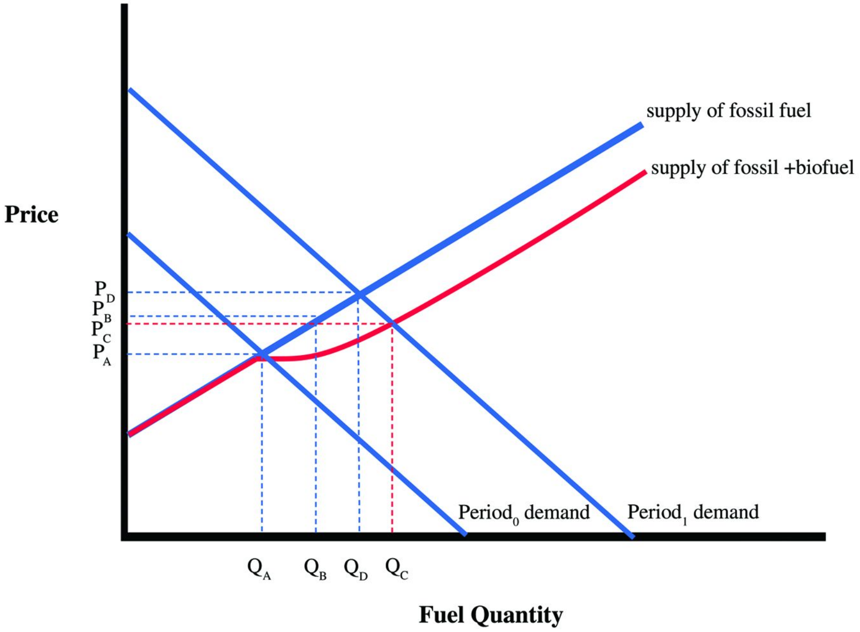

Figure 1

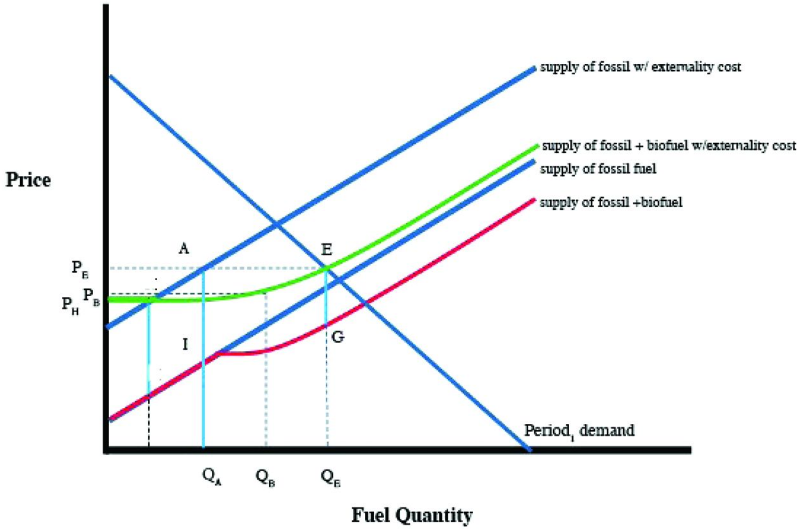

Figure 2

The price of biofuel can be composed of two elements. The segment EG in Figure 2 that represents the externality cost and segment between Q_E and G that represents the private costs, similarly the price of fossil fuel can be decomposed to A*I*, that represents the externality cost and segment between Q_A and I, that represents the private costs of fossil fuel. Note from the figure that following our assumption, the externality cost of fossil fuel is higher and therefore the producers of biofuel are getting a net price that is greater than those of fossil fuel.

These figures show that including the externality cost in assessing fuel may provide *an indirect subsidy to biofuel.* The lower the externality of biofuel, the less it will be taxed—one way to implement the policy is to introduce a fuel tax that is based on fossil fuel and then biofuels will be subsidized by the difference between the social cost of fossil fuel versus biofuels. This analysis suggests that under an optimal policy, when the cost of the externality will be added to the cost of production, total fuel production will decline compared to the case without externality cost ($Q_C > Q_E$) but the biofuel production may increase.

The model in Figure 2 provides the basis for policies economists would love to see. Such policy will include direct pricing of all externalities. If we assume that existing policies address problems of local pollution and congestion, then the major new issues that we address is climate change and to obtain an optimal outcome, pricing of carbon is needed. Economists believe that since climate change is a global externality, having carbon pricing throughout the world will lead to a globally optimal resource allocation (*19*). There are many ways to incorporate carbon pricing and resource allocation. One is a global carbon tax, but obviously it may have political obstacles, as industry is likely to object on the basis that revenues taken from it will move to other sectors. One suggestion is to have a carbon tax, the revenues from which will allow reduction in income taxes (*7*). Since lower income taxes often lead to increased productivity, the carbon tax has the potential to reap ‘double dividends’. Since the carbon tax may have an especially negative effect on the poor because fuel takes up a high share of their income, some of the revenue may be transferred to offset this effect. An alternative approach is to introduce a system where activities that emit carbon would require a ‘carbon permit’, then a government social planner may determine an optimal quantity of carbon which will set a cap on aggregate permits. These permits will be allocated among the population and will be tradable and the price of permits will be equal to the social cost of carbon emissions. Within such a system of cap and trade, both fossil fuel and biofuel users will have to pay (directly or indirectly through the price of fuel) for permits. When biofuel emits less greenhouse gases, the cost of permits for biofuel will be lower and this will lead to the advancement of the technology.

While much of the economics literature on biofuel has a normative emphasis on using it as part of a solution to both growing scarcity of fossil fuel and climate change (*2*), the effort to establish global climate change agreement has made minimal progress recently and a global carbon price is far from reality. On the other end, a wide array of biofuel policies have emerged recently and much of the concern about biofuel seems to address objectives aside from control of global warming, in particular food security, that gave rise to a growing literature on the relationship between food and fuel.

Food versus Fuel

Using land to produce biofuel from plants or trees implies that the benefit of the current use of this land is lost. Production of biofuel may also affect other competing resource allocation, such as water. Thus one of the main areas of research on the economics of biofuel is its impact on land and other agricultural inputs (*13*). Figure 3 depicts the basic economic process through which food and biofuels are related. As before, we assume that the demand of agricultural commodity (corn) for food is negatively sloped reflecting the fact that the value of incremental food is declining, the more quantity of food we have. When food prices are beyond a certain level, there is demand for the agricultural commodity for biofuel. In the figure we depict a joint demand of corn for food and biofuel that is bigger (above) the demand of corn for food below a certain price.

In the Figure 3, we depict the demand for Period_0 as well as the demand for Period_1. If we assume that between the two periods, income increased throughout the world, it would increase both the demand of corn for food and for biofuel. The figure also depicts the supply of agricultural commodity and for simplicity we assume that it does not change between the periods. At Period_0, when the demand is not high, the supply intersects the joint demand for food and fuel at Point A. At this point, there is only production of corn for food and the price of corn is P_A and the quantity is Q_A. At Period_1 where income is higher, the demand intersects at supply at Point B, where the total production of corn is Q_B and the price is P_B, the amount Q_C is used for food, the amount $Q_B – Q_C$ is used for fuel. If biofuel would not have been produced at Period_1, the production of corn would be at Q_E and the price would have been at point P_E. Thus the introduction of biofuel raised the price of food from P_E to P_B, reduced the overall production of corn from Q_E to Q_B, and reduced the corn available for food from Q_E to Q_C. Further analysis using the same logic suggests that the increase in the price and the demand for fuel will lead to the increased overall agricultural commodity prices and production and increase biofuel production but will reduce the agricultural commodity available for food. It suggests that food consumers would lose for two reasons. They will consume less food but they will pay more for it. While the consumers of food may lose from the introduction of biofuel, the consumers of fuel as well as the farmer producing it are likely to gain.

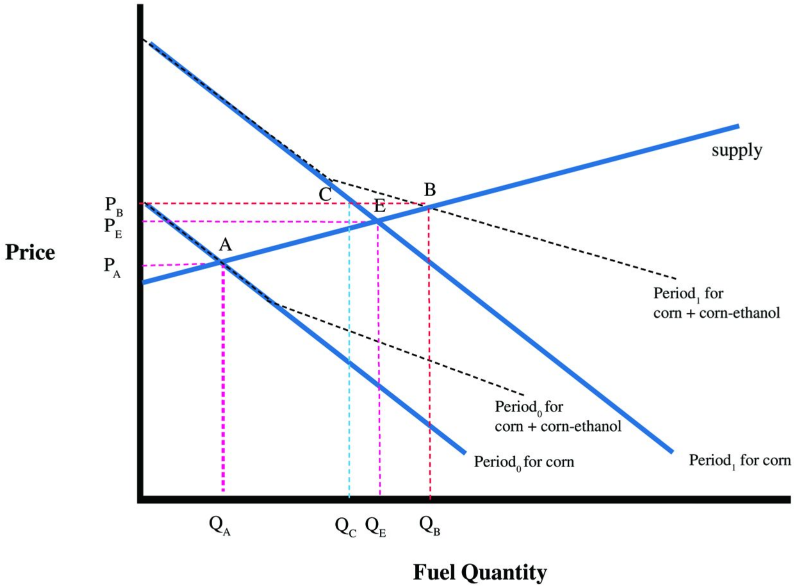

Figure 3

This analysis suggests that when a given input can be used between food and fuel, introduction or expansion of biofuel will reduce the availability of resources for food production. This analysis applies to various choices where a crop is allocated between food and fuel. In the case of corn, the choice is between allocation to produce ethanol, food, and animal feed; between sugar and ethanol in the case of sugarcane; between animal feed and oil or biodiesel in the case of soybean. In all of these cases, the increase in demand for fuel will suggest that overall agricultural production will increase but the amount going towards food production will decline.

The outcome seen in Figure 3 where the introduction of biofuel results in the increased overall production of agricultural commodity and decreased availability for food is not necessarily bad, if the value saved in energy cost and if the gain by the farmers is greater than the extra cost to the food consumer, then there is a social gain. If farmers who are net sellers of food are the poorest segment of the population, they may gain from the introduction of biofuels (*20*). Sometimes the introduction of biofuel may help poor food consumers and in this case, some of the overall gain, in principle, can be transferred to the poor by government income transfer policy and society will be better off. Moreover, most of the 20th century, in most developed countries the agricultural markets tend to end up with over-supply resulting in low commodity prices, low farm income and governments needed to introduce policies that subsidized farming and restricted supply (*6*). If biofuels allow new sources of income to farmers and reduces government subsidies, then it may enhance welfare. Nevertheless, there may be plausible situations where the introduction of biofuels leads to significant reduction of availability for food for consumers, especially the poor ones, which require government intervention including restrictions on biofuel during certain periods. This will be discussed further later.

Economists realize that these tradeoffs between food and fuel may not hold in certain situations. There are hundreds of millions of acres that may have enough rainfall, decent soil and other conditions to support plant production but they are not being utilized for agriculture for some reason. For example Jatropha *Curcas* may be profitable in marginal land in India and Miscanthus may thrive in an area that is now used for rangeland. In these cases, if the production of these crops are not affecting agricultural practices and other resources used for food crop production, then the introduction may not lead to a tradeoff between food and fuel. Note however that energy crops that may be highly productive on marginal land, may be even more productive on agricultural land and in a market economy where farmers have free choice about land use, it is likely that some land that is used for food may be diverted to biofuel.

Another interesting scenario occurs when one takes into account research and development activities and long-run considerations. Research and development is affected by scarcity and as the price of food increases, there will be more public as well as private incentive to improve productivity (*1*). Thus high prices resulting in the production of biofuel may lead to agricultural innovations that may later on result in increased food and fuel production. This can be seen in Figure 4. After the new innovation, the supply is increasing (shifting to the right), the new quantity of corn is presented by QF, the price is PF, food production increases to QG, and biofuel production increases by the segment GF. Technological change and innovation have been major drivers of agricultural prices in the past. Industry introduced new products and farmers adopted new technologies frequently after a period of high prices. Thus, high prices that are associated with the introduction of biofuel may trigger a round of innovation that will soften their impact on prices. Some studies (*18*) emphasize the role of genetically modified varieties in expanding agricultural supply in the past (thus reducing prices) and suggest that if the European Union had lifted the de facto ban on GMO, supply would have increased further and much of the price effect of biofuel on corn and soybean would have vanished.

There is a growing body of literature that uses various types of modeling to assess the impact of biofuel on food prices. Hochman et al. (*10*) surveys the literature and suggests that while economic growth has been the main contributor to the food commodity price inflation in 2008 (contributing 30-35% to the price hike), biofuel was the second major contributor (contributing 15-25% to the price hike), which is in the same ballpark as most other studies. Some studies

(*13*) suggest that biofuel contributed 1- 3% reduction in the price of gasoline, which is within the range of other estimates. So far, there have not been any studies that look at the long-run effect of biofuel, taking into account its possible impact on increased productivity and investment in agriculture. Future expansion of first or second generation biofuel will require assessment of trade-offs on industries resources which biofuel producers share and utilize including forestry, rice production, etc.

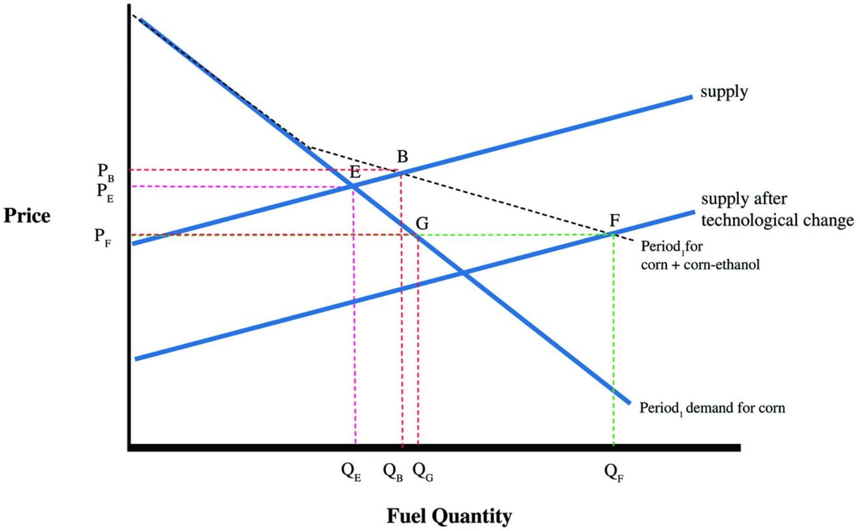

Figure 4

The use of land and other resources associated with the introduction of biofuel also introduced concerns about the indirect land use effect. If the increased demand of agricultural commodities because of the introduction of biofuel leads to the expansion of agricultural supply, there is likely to be an associated expansion of the agricultural land. If some of these lands have been providing environmental services, then the expansion of agricultural production may lead to loss of ecosystem services. For instance, expanding agriculture production to tropical forests may result in deforestation and extra emission of greenhouse gases. In the case of the US, the agricultural acreage has actually shrunk between a peak in 1918 to the present and expansion of agricultural acreage is mostly occurring on land that has been used before.

Much of the debate on the impact of biofuel on greenhouse gas emission is related to what is happening in Brazil. Brazil has gone through a process of deforestation that resulted in a vast amount of rangeland. In those regions there are limited options for income other than forest products, and rangeland is used for cattle and has a relatively smaller area for soybean, corn and sugarcane. Increase in production of biofuel has a direct and indirect effect on agricultural field crops in Brazil but the impact on deforestation is not clear. Economic logic suggests that deforestation will continue as long as the cost of deforestation is low and there is minimal enforcement of forest protecting regulation because the gain for raising cattle and acquiring ownership of land is substantial. Nevertheless, higher food prices may affect at least the speed of deforestation. Quantifying the indirect effect of deforestation and greenhouse gas emissions on biofuels is challenging and has become a major priority for economists and policymakers alike.

Biofuel Policy Analysis

The actual biofuel policy rarely coincides with policy prescribed by economists. As Rajagopal and Zilberman (*14*) suggests, there are several policies affecting biofuel that have been introduced in multiple countries. de Gorter and Just (*4*) emphasized three major policies including mandates requiring a certain mixture of biofuel and fuel within given periods (there may be different mandates for first and second-generation biofuels e.g. 2007 US Energy Bill), subsidies for both biofuel production and investment in biofuel technology and tariffs on biofuel imports. In addition, there are regulations that classify the requirement for biofuels (in terms of greenhouse gas emissions) to meet the standard for inclusion in mandates (Renewable Fuel Standards) and there are other regulations like low carbon fuel standards that set upper bound limits on greenhouse gases emission per gallon of fuel and meeting this limit practically requires the blending of biofuels with fossil fuels.

Policy selection is the result of a political process that reflects the characteristics of the political system and the power of different groups (*16*). Biofuel policy is the outcome of multi-objective political processes where governments aim to achieve objectives that include fuel security, improvement on the balance of trade, the improved well-being of agriculture and the rural economy, maintaining cheap energy prices, reducing government expenditures, food security as well as overall greenhouse gas reduction. The introduction of mandates, domestic subsidies and import tariffs on biofuel reflect the desire of policy makers to improve balance of trade and food security. Zilberman et al. argue that the subsidy to biofuel is at the same order of magnitude as a subsidy (in the form of exemption of payment of royalties) for drilling for deepwater offshore oil (*22*). de Gorter and Just argue that the biofuel subsidy is a transfer to farmers that resulted in overall social loss that is larger than traditional commodity programs (*4*). de Gorter and Just (*4*) as well Cui et al. (*3*) argue that current US agricultural policy aims mostly at energy security and the balance of trade and actually may have a negative impact on greenhouse gases. They argue that the policy can improve by relying only on a mandate without a subsidy. On the other end, Hochman et al. (*8*) suggest that having inflexible mandates may cause food security problems especially in the developing world and thus policy makers will have the option to modify mandates based on states of nature and their expectations regarding food prices. Tyner and Taheripour (*21*) argue that because of viability of energy prices, government subsidies of biofuel should be conditioned upon biofuel or oil prices declining below a certain level. Their analysis suggests another major objective for policy intervention, which is protecting investors against risk associated with biofuel investment, especially in refinery technology and new refineries. To some extent, biofuel subsidies and especially subsidies to R & D and initial investment in biofuel refineries aim (*17*) to develop a new biofuel production capacity. Economists justify subsidization and the protection of new industry by the 'infant industry' argument. One example is theory that second-generation biofuel technology will generate 'learning by doing' and economics of scale and the industry will become competitive in the long run (*5*). However, quite frequently the infant industry argument does not hold and it is a cover for protectionism. The challenge with second-generation biofuels is to know how much to continue support and when to stop.

The RFS2 (*23*) as well as the LCFS (*24*) are policies that are designed with the pursuit of greenhouse gas emission reduction objectives in mind. As we will argue below, they are much less efficient than the carbon taxation but they are feasible politically and the RFS is a part of larger policies, which aim mostly to address energy security, exchange rate and farm income support objectives. The calculation of greenhouse gas emissions under these policies are based on life cycle assessments, namely they include all of the emissions associated with the biofuels including in production of input fertilizers and in processing. Economic theory suggests that under a carbon tax, each polluting activity will be taxed but supply chains are complex; thus transaction costs may be reduced if all of the carbon emissions generated throughout the supply chain are evaluated once at the end of the entire process. An alternative approach is to evaluate greenhouse gas emission upstream, namely producers of coal, natural gas, and refined petroleum products (*12*). Rajagopal et al. (*15*) shows that both policies are less cost effective than the carbon tax in achieving a given level of greenhouse gas reduction. But with the carbon tax, greenhouse gas emission will lead to more emphasis on lowering fossil fuel consumption than on increasing biofuels than under RFS or LCFS. Another major flaw of both RFS and LCFS is that they are partial solutions to a global problem. So even if California can reduce greenhouse gases emitted by liquid fuels by relying on clean fuels (say, sugarcane ethanol) the use of polluting gasoline from tar sand, will shift to China that does not have similar regulation. Nevertheless, both policies contribute to the development of the biofuel industry and RFS in particular, is contributing to achieve fuel security.

One of the most controversial aspects of both RFS and LCFS is the extent to which indirect land use emissions will be accounted for within these policies. In principle, expansion of biofuel will increase agricultural production that may expand greenhouse gas emission. However, Zilberman et al. (*22*) argue that one type of indirect effect necessitates the consideration of other effects. The magnitudes of these effects are uncertain and unstable. As we argued earlier, it is not clear to what extent the prices of agricultural commodities contribute to deforestation. Agriculture prices are likely to contribute to increased production of soybean in Brazil but as long as deforestation is not regulated in Brazil, there are many incentives to deforestation because of the private long and short-run term gains associated with it. The computation is difficult and time-consuming. There are also concerns that farmers in the US will be responsible for activities of third parties. Furthermore, developing countries like Brazil develop policies that aim to protect the forest and that may affect the indirect land use. All of these complexities may result in transaction costs that may hinder investment in biofuels, thus one alternative is to develop regulatory limits that are more binding over time.

It is likely that the first and especially second-generation biofuel will improve over time the more experience with their use is accumulated. But investment in both research and development is likely to decline with uncertainties about the technology thus policy makers have a challenge to develop policies that will reduce environmental risk and at the same time enable technological innovation that will be beneficial in the long-run.

Adoption and Implementation

Much of the economic research on biofuel is numerical and aims to assess where and how the technology will be implemented. Economists have developed a wide variety of quantitative tools relying on different assumptions, some to assess the future of biofuel under different policies and its impact on agricultural commodity prices, fuel prices, food prices and others the economy in general.

Some of the models are linked to geographic information systems and can predict when and where different types of biofuel can be produced under various conditions. One model that was especially designed to assess the impact on biofuel is 'BEPAM' [Biofuel and Environmental Policy Analysis Model (*11*),]. This model demonstrates that alternative parameters for policy regulation will result in alternative land use patterns and greenhouse gas emissions. For example, sugarcane ethanol is less likely to figure prominently in the production of biofuel if stricter low carbon fuel standards criteria are enforced and innovation lowers cost of second-generation biofuel or if second-generation biofuels benefit from extra subsidization. BEPAM predicts location patterns of biofuel in the US under different policies and the impact of greenhouse gases and other environmental amenities. According to this model, agricultural production in the US will be expanded under several scenarios but it appears likely that the second-generation biofuel crop will be grown in areas that are currently growing crops for food.

The quantitative models are facing multiple challenges assessing the prices of first and second-generation biofuels in the future, assessing the dynamics of crop yields, assessing the growth of demand, etc. High growth in the productivity of corn, for example suggested by Miranowski (2007) may lead to continued emphasis on corn ethanol, especially when combined with biofuel from corn stover. On the other end, high rates of population growth and increased demand for food without an increase in agricultural productivity, may limit the growth of agricultural and crop-based biofuel.

Another set of issues that will affect the fate of biofuel relates to the ability of biofuel to be integrated within the liquid fuel supply chain. Currently, one barrier for the adoption of ethanol is the blending wall, where a maximum of 10% of ethanol can be mixed with gasoline for use in vehicles. Raising the wall to 15% will expand the use of ethanol, which depends on regulatory choices. Introduction of a further expansion of the use of ethanol will be possible if manufacturers in the US will introduce in flex cars, and fuel companies will start selling E85. This depends on the profitability on how competitive is ethanol with respect to other fuels, to what extent are oil companies and the public are confident that it will be a permanent solution and if it is worth a long-term investment. Presently, it is clear that biofuels will play a role in the future but to what extent they will be utilized, and what form it will take, remains unclear.

In addition to uncertainty about the adoption of biofuel by consumers, there is uncertainty about adoption by farmers. There is a large body of economic literature (for example, ref (*11*), and a significant amount of empirical experience on the introduction of new crops. This literature suggests that new crops are introduced either by vertically integrated supply chains where large companies produce a crop, process it and ship it or by contracting, whereby major companies process production technologies at the farm level, which they then process and sell to consumers. The large scale production of both poultry and swine was the result of development of efficient production and processing technology that were spread out by supply chains that relied on either vertical integration or contracting, providing a lot of valuable lessons on the introduction of biofuel.

Finally, the introduction of biofuel will be affected by the behavior of OPEC. Hochman et al. (*9*) argue that OPEC behaves as a monopoly of nations, where it charges monopoly pricing for oil in the importing countries but subsidizes consumption of fuel in OPEC countries (it is sold below the world price). While in the short-run OPEC may respond to the introduction of biofuel by increasing exports making biofuel less profitable, in the long-run it is likely that OPEC may respond by reducing its exports to increase the price of oil and OPEC revenue. Thus further modeling of OPEC is needed to assess the overall impact of biofuel on energy prices and greenhouse gases.

Conclusion

A few factors will determine the future of biofuel. The less costly second generation technologies are, the brighter the future. It is important that these technologies are relatively cheap and as clean as possible. Another is the dynamics of global economic and population growth and its impact on the demand for transportation and energy. Third is the productivity of agriculture. The more productive agriculture is, more resources will be available for biofuel. Fourth is the issue of policies. To what extent will governments have the political will to invest in technologies in second and third-generation technologies as well as their willingness to subsidize the beginning stages of adoption. A related issue is entrepreneurship by companies, to what extent will oil companies and others, will venture to invest in biofuel.

Another issue is environmental policy and in particular land use regulation. To what extent will governments allow expansion of biofuel to agricultural land and in particular, non-agricultural land. To what extent land that was initially allocated to forest will be converted to biofuel and policies will enable expansion of biofuel to rangeland and forests. Fifth is the extent and evolution climate change and the capacity of biofuels to effectively reduce greenhouse gas emission relative to alternatives. Sixth is the development of alternative sources of energy for transportation; to what extent will be advances in batteries and other alternative energy sources to make electric cars competitive with biofuel.

It seems in the next 25 – 50 years biofuels will expand and investment in second generation will provide some fruit. Prices of fuel are likely to be in the range that makes at least some sort of biofuel profitable. Increased concern about climate change is likely to lead to policies that will provide better incentives to invest in cleaner biofuels.

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Chapter 10

Securing a Bioenergy Supply: UK and US

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Biomass is considered to be a low carbon source of fuel, where the carbon sequestered by during crop growth is released during combustion. The energy available from biomass is considered virtually 'carbon neutral', with the exception of some emissions incurred through the cultivation, transport and production of the fuel. Biomass is therefore considered to play an important long-term role in reducing future global GHG emissions (*1*) when used to produce transport fuels, heat, electricity, lubricants, food, building materials, chemicals and more (*2*). One of its key advantages over other renewable energy sources is that it can be stored to provide energy when it is required. In developed countries there is growing interest for increasing the contribution of biomass-based primary energy production to the overall energy mix. This is expected to reduce the overall emissions from the energy sector, fulfilling national emission saving targets, as well as increasing energy security in the face of a potentially turbulent future for cost and availability of fossil fuels.

In this chapter we seek to address the issue of securing a reliable biomass supply. We examine the main restrictions to accessing current supplies and stipulate the limitations to producing and accessing a supply in the future. We will also consider the possible interactions between a limited supply,

In Perspectives on Biofuels: Potential Benefits and Possible Pitfalls; Taylor, C., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

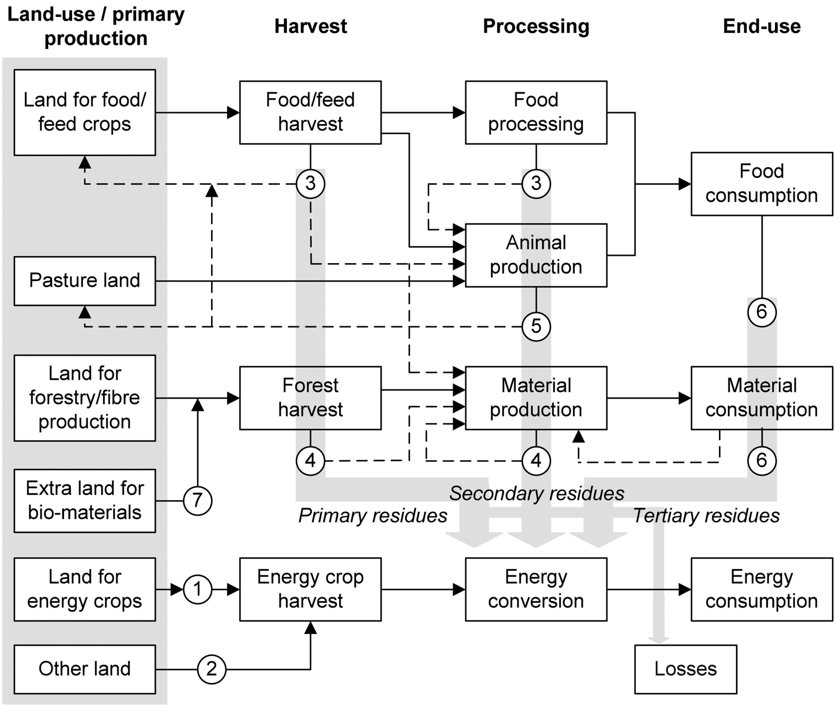
and a potentially unlimited demand for biomass. As there are variety of potential end-uses of biomass, there may be a ‘rush for biomass’ if more biomass-to-energy systems become established. Examining biomass supply is key to understanding the limit of what can be produced, and where. This is particularly important given the predicted global population increase and associated predicted 70% global increase in food requirement (*3*) and the restriction in land availability.

Introduction

Biomass resource assessments have discovered that biomass is a complex and diverse resource. As biomass is a product of vegetative growth, the makeup of the biomass supply will vary across regions. The supply will be affected by the terrain and land use, as well as population size and density. The long-term feasibility of any biomass plant will depend on a reliable supply of a given type of biomass that is suited to the conversion technology available. Often, the supply will need to comply with a given specification of moisture content, energy content and form. It must also be provided at the right price. This can be both a challenge and a constraint to the development of the bioenergy sector.

There are two main issues of biomass supply. The first is that there is **a limited supply of biomass**. This is true in both a national and global sense. There are three main types of biomass: purposely grown energy crops, residues from other industries and wastes (Figure 1). Purposely grown energy crops rely on land to be available for their cultivation, as well as commitment by farmers to grow them. Land is a limited resource, and there will always be an opportunity cost of using it for one use instead of another. Biomass resources that are by-products of other industries include agricultural residues such as straw, or sawdust from the timber industry. In these cases there are few opportunities for increasing the production of these resources as they are dependent on the behavior of another industry. Likewise, biomass that can be found in the waste stream is limited by the production of waste which governments and policy makers are currently aiming to reduce. Both by-products and wastes are, however, being produced and could therefore potentially be diverted for bioenergy purposes.

The second issue is that there are **constraints on the supply of biomass**, as not all biomass produced may be available to the energy sector (*4*). Different countries may have different logistical challenges to accessing their potential biomass resources, which may involve collecting from highly dispersed origins or working in environmentally sensitive areas. There may also be complicated issues of market competition, due to which biomass utilized for energy use may have an adverse effect on other industries.



The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The grey arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

Figure 1. Variety of Biomass Sources. Adapted from (5).

Bioenergy Policies

In both the US and the UK, there has been a growing demand for biomass since it received increased attention in the early 2000's. In the US, bioenergy policies have focused on vehicle biofuel production in a bid to decrease the country's increasing dependency on imported oil (*6*). The publication of the Biomass 'Vision', produced by the Biomass R&D Technical Advisory Committee in 2002 (*2*) outlined their "30 by 30" goal, envisioning that by the year 2030 a third of US petroleum consumption will be replaced by bioethanol. This goal was then verified by the Energy Independence and Security Act (EISA) of 2007, proposing that 20% of petroleum would be displaced by biofuels by 2017 (*7*). The EISA first introduced GHG reduction targets for biofuels; however these were not enforced until 2010, with the introduction of the Renewable Fuel Standard (RFS2, (*8*)).The "30 by 30" goal will require 36 billion US gallons (or 136 billion liters) of biofuels to be produced by 2022. This will include 21 billion US gallons of 'advanced biofuels' (*9*). The RFS2 expanded the original bill to include biodiesel, of which 1 billion gallons should be produced by 2012, where only 0.5 billion gallons was produced in 2009 (*9*).

In contrast to the UK's policies have been more focused on the renewable energy sector as a whole, rather than specifically biomass-based energy. In the UK, biomass received increased attention after the publication of the original 2003 Energy White Paper (*10*), where biomass was identified as having a significant role in the future energy mix of the UK. The implementation of biomass-based energy has been planned through a series of strategies (Figure 2). Energy security was listed as one of the four distinct areas of concern, as well as the need to revise and renew the energy infrastructure in the UK, tackle global climate change and fuel poverty. The UK was then the first country to sign up to a legally binding Climate Change Bill, which provided targets for progressively reducing greenhouse gas emissions by 60% by 2050, using 1990 emissions as a baseline (*11*). The latest UK Renewable Energy Strategy has since revised this to a challenging 80% saving by the year 2050, staging the approach in 5-year targets (*12*). The UK's Climate Change Bill was translated into the Climate Change Act in 2008 (*13*) and concerns national greenhouse gas saving achievements collectively, from the use of renewable fuels as well as energy efficiency.

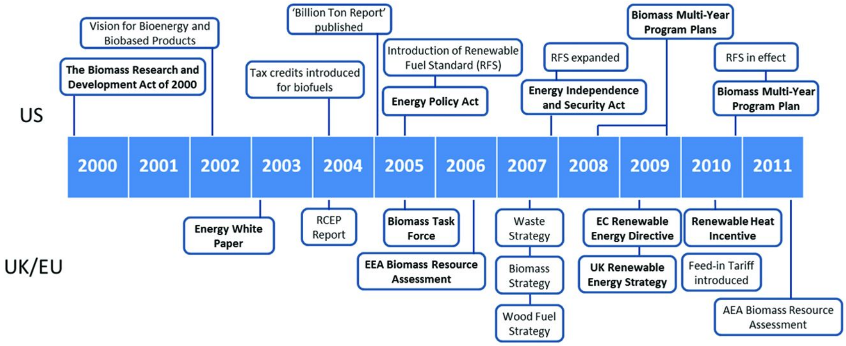


Figure 2. Timeline of biomass policies, strategies and assessments in the UK and US since 2000.

UK bioenergy targets include the Renewables Obligation (RO) and biomass Renewable Transport Fuel Obligation (RTFO). The RO's original aim was that 10% of all electricity will be generated from a renewable source by 2010, and 15% by 2015. The European Commission's Renewable Energy Directive (RED) (*14*), sets overarching targets that the EU will produce 20% from renewable resources, including a minimum 10% from renewable transport fuels. The UK is committed to a 15% contribution of renewable energy generation (*15*). This translates to approximately 224 billion liters, based on current gross energy consumption of 21,227 TWh in the EU_{27} (*16*). [This assumes an average energy content of 42 MJ/litre for biodiesel (*17*) and 21 MJ/litre for bioethanol (*18*), and a share of 61%

and 39% for biodiesel and bioethanol, respectively (*19*).] The RED also states that biomass is not grown on biodiverse, protected or endangered lands (*14*).The renewable energy targets in the UK do not specify the type of technology that should contribute to the energy mix, however it is envisioned that biomass will deliver about 30% of the renewable target (*20*).

It is difficult to estimate the quantities of biomass that are required to fulfill emission saving targets of the UK, mainly because it is not known how biomass will contribute to these targets. Estimating the required biomass supply for the biofuels targets is also difficult as, although we can estimate the biofuel yields achieved during conversion and predict the future demand for liquid transport fuels, there are a range of potential biomass feedstocks from which we can produce biofuels. There is also the possibility that biofuels, and biomass, is exported from other countries in order to reach the production targets.

The Use of Land

Land is a limited resource, and there is an opportunity cost of using it. Land is generally limited to one use, whether this is for housing, infrastructure, forests, agriculture or 'nature'. The 'cost' of using it is therefore being unable to use it for something else. There is a risk that the increasing demand for biomass may be met through expansion of agricultural land (*21*), which will come about through destruction of natural habitats. Such natural areas may be areas of high biodiversity or carbon stock value, their loss due to biomass production therefore having an adverse environmental and social impact. Indirect land use change can occur within and between countries, and is generally a complex impact to calculate, predict, and validate (*21*). Deciding how much land could be made available for biomass production within a country depends on current uses and demand of land. This will range greatly across countries and regions, and some areas may be more at risk from adverse effects of indirect land-use change than others (*22*).

As well as purposely growing dedicated energy crops, there are opportunities to source biomass from existing uses of land, whether this is waste, low-value biomass, or residues from processing other goods. This section examines the areas and types of land resources available, as well as identifying any scope for 'unused' land that could be converted to energy crop production.

Land Use in the UK and US

The United States has a population of five times and a land base approximately 38-times larger than the UK (almost 916 million hectares (US), compared to approximately 24.5 million hectares (UK)). The land base of the UK is divided across four countries: England (54%), Scotland (32%), Wales (8%) and Northern Ireland (6%). The land base of the US comprises North America "48 States" (81%), Alaska (19%), Hawaii as well as several territories in the Caribbean and Pacific (together less than 1%). While forestland and grazing forms the largest uses of land in the US (*23*), the UK Countryside Survey of 2000 (*24*) records that the majority of the UK landscape belongs to agriculture (Figure 3).

The Agricultural Sector

Agricultural land is typically classified as land used for food production, including cropland and grazing land. It can also be used for horticultural purposes. In both the UK and US, a significant area of land is devoted to livestock pasture; the main difference is the US has a large proportion of naturally occurring grasslands, where the UK is mostly managed grassland.

In both the UK and US, some areas of existing cropland are not used. Such fallow areas have been targeted by many resource assessment reports as potential areas where bioenergy crops can be grown. In the majority of cases the land is left fallow for economic reasons, whether this is because of poor growing conditions or governmental incentives. Over the years, there have been financial incentives for leaving land fallow, whether for minimizing erosion, improving soil carbon content in the US (*4*), or reducing excess food production in Europe (*25*). In Europe, however, such incentives have been removed since 2009, therefore set aside land has decreased, despite there being a campaign for maintaining it for biodiversity reasons (*26*). In 2010, it was recorded that 174,000 ha of cropland were uncropped, in comparison with 663,000 ha in 2006 (*27*), a decrease mostly likely due to high cereal prices. A similar relationship can be observed in the US, where the areas of idle land have been decreasing since the 1980’s, though the Crop Reserve Program (CRP) program has reduced this decline. In 2002, idle land totaled 40 million acres (16 million ha), and 85% of this was land enrolled in the CRP (*17*).

Grazing land may also be a potential area for expansion of bioenergy crops; however this can put pressure on livestock farmers. An estimated 19,400 ha of rainforest has been destroyed annually since 2007 to expand pastureland and soybean cultivation for animal feed (*28*). The global demand for meat and milk is expected to double from 2006 to 2050, particularly in the developing countries (*28*). Therefore, one can assume grazing land is a highly sensitive area of land use. Grassland, pasture and range covers a significant area (31%) of the US, there is also some cropland pasture, which tends to be rotational (*23*). Grazing land is the largest single use of land in the UK, covering 11.5 million ha (*27*).

The Forestry Sector

Forestland is one of the largest uses of land in the US, covering 33% of the total land area. Two thirds of this forest land is regarded as highly productive ‘timberland’; the remaining, less productive area regarded as ‘other’ forestland, being only suitable for grazing or non-industrial uses (*4*). In the UK, forestry represents 12% of the nation’s total land. There is no distinction between ‘timberland’ or other woodland in the UK, though plantation forestry is common practice in the UK, and tree crops are managed to maximize timber volume production, typically under a clear-fell regime (*29*). About 60% of the woodland is populated by conifers, particularly in the northern parts of the UK (*30*). Woodlands in the US tend to rely more on natural regeneration, and often follows a continuous cover system with a mixture of softwood and hardwood species (*29*).

Urban Land

Though the area of land dedicated to urban is much less than 3% in both the UK and US, this is where the population, commerce and industry dwell, and hence, a significant amount of waste can be sourced from here. Biodegradable wastes are however often a product of the agricultural or forestry sector, including materials imported from overseas.

A major source of waste from the urban sector is municipal solid waste (MSW), which is waste collected by the local authority from the residential districts. An estimated 55% and 54.3% of MSW waste is landfilled every year in the UK and US, respectively (*31*, *32*). About 60% of this is estimated to be biodegradable (*32*, *33*). Due to this, landfill is currently the most significant source of biomass-generated energy in the UK (*34*), and the second most significant source in the US (*8*). This resource can, however be used more efficiently, and landfill sites are a major source of methane. Under the EU Landfill Directive (*35*) all new landfill sites are required to carry out landfill capping and methane capture with preference for energy recovery, and these restrictions have so far reduced emissions from landfill by 61% between 1990 and 2002 (*36*).There is no similar landfill target in the US; the main emphasis is to reduce emissions from landfill sites by encouraging the recovery and beneficial use of landfill gas (*37*).

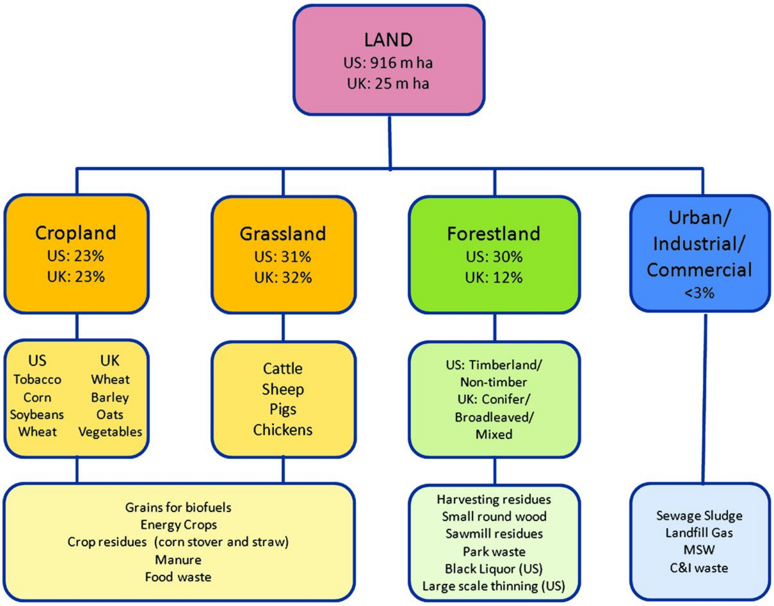


Figure 3. Land use and biomass resources in the US and UK. Note one omission 'special use' land, such as natural areas, recreational areas, and miscellaneous land which represents 13% in the US (23), and 31% in the UK (24). The land area for the US is based on "48 states" (23).

Current Use of Biomass for Bioenergy

In both the UK and US, biomass is the largest contributor to the national renewable energy generation. In 2009, renewable energy contributed 8% of total consumed energy. Biomass contributed 50% of this, including 20% from liquid biofuels production. The remainder was provided from landfill gas and woody material (*8*). Total bioethanol production was 845 trillion Btu in 2009, or 10.8 billion gallons. In the UK, renewable energy provides 2.2% of domestic energy (*16*), with biomass contributing 81% of this, including a contribution of 16% from liquid biofuel consumption (*38*). The major biomass resource is landfill gas, which is used to produce both heat and electricity (*34*). In comparison to the US, the majority (71%) of renewable energy in the UK is used to produce electricity (*38*).

The Potential Biomass Supply and Its Constraints

A few studies have aimed to quantify the potential biomass resource of both the UK and US, and globally. In August 2011, the United States Department of Energy sponsored an update to the original 'Billion Ton Report' of 2005 (*4*, *39*). The original report, produced by the United States Department of Agriculture (USDA) and the United States Department of Energy (DOE) was a strategic analysis to whether the US could provide enough biomass to satisfy the '30 by 30' goal of the Biomass 'Vision' (*2*, *4*, *39*). The report provided an assessment of the USA's current and future potential biomass resource potential and estimated that an annual biomass resource of up to 1.4 billion tons could be sustainably collected by the year 2030, from the forest and agricultural sectors. This does not include biomass which is currently being used by various industries suggesting that it is biomass that could be made available for renewable energy purposes. Using conservative estimates of energy content, this could equate to 21,000 PJ primary energy. Of the same order a further study suggests that there is a primary energy resource of 94,000 PJ/y in the US, 12.5% of which could be available for bioenergy purposes (11,750PJ),(*40*). Ambitious global estimates by the IEA state that 1,500,000 PJ will be available by 2050 (*3*). The 'Billion Ton Update' of 2011 provided a more in-depth analysis on a county-by-county basis, with consideration of economic supply curves and more vigorous assessments of resource availability (*39*). The analysis estimated, at a biomass price of $60 per dry ton, that the biomass resource was limited to between 767 and 1305 million dry tons per year, depending on various assumptions on crop yield productivity by 2030 (*39*).

Since 2005, a number of reports have attempted to assess the biomass resource potential for the UK (Figure 2). In order to be adopted bioenergy has to be economically competitive with the alternatives such as fossil fuels. This competitiveness will be related to their constraints and barriers. The most recent, by AEA Technology, analyzed the quantity of biomass that is likely to reach the market despite several barriers and competitors (*41*). Focusing on technical, political and economic constraints, they estimate that the potential biomass resource could reach 780 PJ/y in 2030 (*41*). The biomass resource assessments include projected increases in biomass production over time; this relying on intensified crop production and increases in arable and energy crop yields (*4*). To some extent, an expansion in land for energy crop is required, though this is limited, and should not hinder food production, or adversely affect areas of high carbon stock or natural habitats. It is important to note that the resource estimate is primary energy; the actual energy delivered will depend on whether the biomass was used for heat, electricity or biofuel production, also financial constraints are applied and more could be extracted if the cost of energy were to rise. As a comparator, the UK primary energy demand was approximately 9,240PJ in 2009 (*38*), therefore biomass could potentially competitively supply just under 8% of the UK's energy. [This calculation is based on the total demand being 220,000,000 tonnes of oil equivalent with a conversion rate of 42GJ energy per tonne.]

The range of potential feedstocks highlights that biomass is a multifaceted and versatile resource. The availability of these materials is intertwined with activity in other major economic sectors: agriculture, forestry, food processing, paper and pulp, building materials etc. (*42*). Hence supply-chains for biomass feedstocks are correspondingly complex. There are also various constraints which can arise from political, economic, social, legal, technical, environmental and other factors. This section outlines some of the main competing uses and constraints which limit the potentially available biomass resource.

A critical factor that affects biomass availability is accessibility. The dispersed nature of biomass represents a key constraint to most biomass sources where there is no central collection point. Biomass may be impractical to collect due to its location with the economics of collection also not favorable. Another consideration is the rural location of the biomass supply as often there is insufficient local end-user demand for the resource (*43*). Social constraints may include such factors as perceptions of food crop displacement or the visual aspect of tall energy crop growth. Economic factors are also critical as biomass may have a higher value, and competition for an alternative use in another sector, or low density biomass can be expensive to transport. Contaminated feedstocks such as wood waste could be considered an environmental constraint. All of the above gives an indication of some of the possible restrictions on the availability of biomass, which are explored further below.

The Agricultural Sector

Agriculture provides a wide range of products; hence there are numerous competing uses for the biomass produced. These arise primarily from using agricultural land for food and feed crops, and livestock farming. Competition from other crops and investments is seen as a critical barrier to increasing the biomass supply for energy use (*44*). Intensifying productivity on agricultural land is necessary to ensure potential food and fuel production, though this has a limitation. The economic constraint of using farmland for higher value food products is a key limitation to the development of bioenergy. Global commodity prices and markets for biomass resources also affect the security of supply, with the availability of annual crops being affected by the market price obtainable (*45*).

The availability of crop residues is affected by a variety of factors, which include the type of crop, residue yields, harvesting methods, alternative uses for residues, and farm management choices. For example, an important use of straw in both the US and the UK is for both animal feed and animal bedding, which is apparent given the high amount of livestock farming. Straw is fed to livestock as a source of long fiber, an essential part of the cattle and sheep diet, and used for dairy, beef, pig, poultry and horse bedding (*46*).

A key environmental concern from accessing agricultural resources is the impact of residue removal from soil, which is implicated in poor soil quality and soil erosion. This is a significant issue in the US, where either minimal tillage and residue retention is practiced in order to maintain good soil conditions (*4*). Crop residues, such as corn stover and straw can be defined as an agricultural by-product of corn, cereal and oilseed production, which are grown primarily for their grain for the food market. Residues are often ploughed back into the soil to improve soil fertility and structure. As they are valuable source of nutrients and minerals, consideration must be given to the cost of providing these nutrients in the form of artificial fertilizers, which have become increasingly expensive (*47*). There are no recommended guidelines on how much crop residues should be returned to the soil to maintain soil function; this will range between area, price of straw, price of fertilizers and soil quality.

A logistical constraint of accessing crop residues is the cost of bailing and removal. The low bulk density of straw means that it is generally considered uneconomic to transport straw over long distances. Similarly, the net energy benefit is greatly reduced when transporting biomass over distances.

Other environmental constraints for agriculture include land-use constraints, including avoidance of expansion into nitrate vulnerable zones, areas of outstanding natural beauty, national parks, ancient woodland, and other protected areas. In the UK the cultivation of energy crops is restricted to areas of agricultural land (*48*). The local climate, topography, geography, land type and grade are all key factors in determining the suitability for biomass cultivation. For example, some permanent grassland is considered unsuitable for arable cropping, somewhat due to fertility, but mainly due to physical limitations that impede the use of machines, such as rough and steep terrain, stones, boulders and very poor drainage (*49*). Farmers may obtain higher returns for certain livestock, soil type and quality, and environmental stewardship.

Farmer choice can potentially be a key constraint to the expansion of energy crops. The nature of bioenergy crop contract periods will not likely be similar to those of arable crops, as the crops are in full production for up to 20 years (*50*). There is some scope for governmental incentives to be implemented to promote the uptake of perennial crops, and to some extent this has been successful in both the US and UK.

Social and ethical concerns have arisen regarding the use of agricultural land for bioenergy production. The world food demand combined with increased competition for land is still a key concern for many Governments (FAO, 2008). Other social constraints relate to the siting of energy crop plantations and conversion facilities, and the effect of transport in rural areas.

Animal manures and slurries are an abundant resource arising from livestock farming, which must be disposed of in an environmentally responsible manner. They are frequently spread on land to return valuable nutrients to the soil. This practice has been done for centuries and represents the main competing use. However, this risks nitrate leaching particularly in nitrate vulnerable zones, and the release of nitrous oxides after land-spreading contributes to greenhouse gas emissions. A more appropriate solution may be to process animal wastes and residues through anaerobic digestion, which not only allows for energy recovery but also produces a better quality fertilizer by-product (*51*). High capital costs and public acceptability are likely to be the main barriers to implementing this technology on farms. As a waste stream the alternative end uses are limited, with those manures and slurries not used as feedstock generally sent to landfill or incinerated.

The Forestry Sector

The forestry sector provides a range of wood fuel sources, including stem wood, forestry residues, arboricultural arisings, and sawmill co-products. The market for bioenergy provides an opportunity for forest industries to receive income from its residues, providing a market for its by-products and increasing its competitiveness. Since forestry materials arise as a consequence of other forestry activities, the marginal energy costs and emissions from its production are minimal (*52*). There are, however, several competing uses for forestland derived feedstocks; with the largest consumers being wood based panel and paper industries (*53*). There are also some technical constraints to accessing forest biomass from steep terrain and mountainous areas, though these are often due more to economic reasons, as the technology is available, however costly to run (*4*)

Stem wood is the main valuable product obtained from plantation forestry. Its high economic value as wood for use in construction and other wood-based industries is the main constraint to its use for bioenergy. Suitable biomass resources are limited to branches, treetops, and poor value small round wood that result from traditional logging industry activities. Also, woody biomass can also be derived from large scale thinning events in the US, undergrowth in forests and wood from pest or storm-damaged woodland (*4*, *52*). Some biomass can be derived from thinning events performed in conventional plantation forestry; however a competing material for this is the pulp and paper industry.

Forest harvesting residues, such as branches and tips, do not have a current market in either the US or UK, therefore there has been growing interest in this material for biomass. Particularly in the US, sometimes these residues pose a fire risk, and there is a requirement to remove them. There are, however, significant economic constraints to this, not dissimilar to the concerns with crop residues in the agricultural sector. As forest residues decompose they return both nutrients and organic matter to the soil and there is concern that removing these residues may impact on future soil quality and soil organic carbon sequestration, as well as biodiversity and sediment transport to water courses (*54*). Harvesting residues are also left on the site to protect the soil from heavy passing machinery. The key

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constraint is to determine the proportion of residues that can be removed, while preserving ecological stability and minimizing soil impaction. Next, one must consider economic sustainability with respect to existing markets. Harvesting these residues requires the use of extra harvesting machinery that can be costly to run. Forestry residue processing is not a developed industry so economic constraints are difficult to assess.

The lack of an end-user market to match the scale and location of the resource pre-empts sustainable development and can be considered a social constraint (*43*). Barriers to implementing the use of forest residues are the need for substantial infrastructure development for residue collection and processing, although these could be addressed through sufficient market demand, which is presently restricted by high capital costs.

Smaller woody resources include arboricultural arisings, which are defined as material that becomes available as a result of tree surgery in, for example, parks, streets, school grounds and private gardens and from site clearance for building, construction and road developments. These residues are usually left on-site in the form of chippings or removed to landfill, with only a small proportion currently used in energy end markets. Competing uses for arboricultural arisings are limited principally to the use for composting. Sawmill co-products in contrast have numerous uses and have the clear advantage of being located in a central location.

Post-Consumer Waste

Post-consumer waste is generated from a wide variety of industrial sectors and households. This is generally regarded as a 'renewable resource', though this is open to debate. Waste can be defined as 'any substance or object which the holder discards or intends or is required to discard' (*55*). This definition covers a wide range of different sources (and forms) of material, which includes the biodegradable fraction of municipal solid waste (MSW), waste wood, commercial and industrial (C&I) waste, waste fats and oils, sewage sludge, and landfill gas. Some waste streams are more readily available than others such as landfill gas and sewage sludge as these already go to a central collection point. In contrast other waste can be very dispersed and difficult to collect. A critical barrier to utilizing waste is therefore the development of a cost-effective, domestic and commercial collection infrastructure.

A constraint to using waste as an energy source in the EU is that this use falls below other waste management priorities in the traditional waste management hierarchy. Consequently its practice can only be considered sustainable when embedded within a waste management framework with strong reuse and recycling objectives. The competing uses for waste are therefore limited at the point of which energy recovery is preferable. Furthermore in many situations although composting maybe favored, anaerobic digestion improves the quality of the fertilizer by-product in addition to energy generation, producing a double benefit.

Economic constraints are likely to reduce over time as the alternative cost of landfill gate fees and taxes continue to rise. There is also legislation in place which aims to reduce the amount of waste sent to landfill (*35*). Social constraints on acceptable sites for new developments are potentially the single most important barrier. This is apparent due to public perception of waste processing facilities being located close to urban dwellings.

For waste to be effectively utilized source separation is required, which constrains its use to areas where material recovery facilities are available. The cost of separating out the waste wood stream can be expensive which constrains the economically sustainable resource. Additionally the composition of waste effects how it can be processed which can limit the potential end-uses. Another key barrier is thus the high cost of developing environmentally suitable processing facilities, e.g. Waste Incineration Directive (WID) compliant (*56*).

Concluding Remarks

Biomass is a low carbon renewable energy resource that can minimize some of the intermittency problems associated with other renewable energy supplies. It is the biggest contributor to renewable energy within both the US and the UK. However, it is not an unlimited resource and there are other competing demands for the biomass resource. There is a limit to what biomass can supply and a limit to the land on which biomass is grown. As population increases the pressure on land is likely to increase, making high yielding biomass options of even greater interest. Within this chapter we have estimated the available energy from biomass in both the UK and the US. A direct comparison is difficult, as reporting methods vary; some citing energy availability in terms of Joules, and some in the mass of biomass available. Whilst estimation of the energy availability of biomass is certainly useful it is often difficult to estimate as the energy output will vary significantly depending on the conversion technology and use. Therefore, there is a clear need for more transparent data calculation and reporting. Never the less, a range of 460-780PJ per annum potential primary energy production is given for the UK for 2030, and a range of 21,000-117,500PJ per annum potential primary energy is given for the USA.

Biomass is a significant resource in both the UK and US though it is made up from a complex and diverse range of sources (Figure 3). Between the two countries, the biomass resources are similar in nature; though differ in quantities and significance. The biomass resource base is composed of a wide variety of primary, secondary and tertiary sources from the agricultural, forest and urban, industrial and commercial sectors, where it is found as ‘post-consumer’ waste (*4*). Primary sources are those that are extracted directly from land, such as arable and energy crops and forest residues. Secondary sources are often found as residues from processing stages, such as sawmill residues or co-products from biofuel production. Tertiary sources represent wastes, such as MSW or manure. Each type of biomass resource may have particular issues which arise from competing uses and constraints to sourcing them. All sources of biomass face constraints when looking at their potential use as bioenergy. Critical is its availability as biomass resources are often dispersed and not close to habitation or a central collection point. Collection and use therefore forces both environmental (in terms of the energy required to collect and use) and economic considerations and constraints. Bioenergy sources that may be found within higher density areas, such as municipal solid waste, are constrained by environmental concerns and compliance with, for example, air pollution and incineration legislation as well as an overarching aim to reduce waste through re-use and recycling. Never the less, within the UK this is the significant source of bioenergy.

Crops that require high levels of fertilizer inputs are unlikely to be competitive in terms of energy or economics; nor are they available for use on some of the most nitrate vulnerable areas in the UK. Competition with land for food is an energy, economic and a publically acceptability constraint for many energy crops. As a result the focus is on second and third generation bioenergy, where co-products and wastes as well as specific bioenergy crops are favored over the more traditional corn and oilseeds (first generation). Nevertheless, these do also have potential problems associated with reducing soil nutrients, energy input, costs, and also with land competition.

Key to the success of bioenergy is that it can be used to store energy and that the biomass can be used to produce such a diverse array of energy and fuels using a wide variety of technologies. This diversity will enable a range of crops and residues to be used and this variety, despite the wide array of constraints, may be key to its success.

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Chapter 11

Biomass Sustainability Standards: Towards a Credible and Feasible Measure of Biomass Sustainability for U.S. Bioenergy Policy

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In order to mitigate greenhouse gas emissions, facilitate energy independence, and stimulate rural development, U.S. bioenergy policies have increasingly emphasized combustion and conversion of biomass to electricity and fuels. This shift in federal and state legislation, however, raises new questions regarding exactly how "sustainable" biomass feedstocks from actually can be if forests become overharvested, or cropped lands follow the commodity status quo. The most prevalent issues include water quality and quantity, erosion, biodiversity, and threats to food security. As a result, several biomass sustainability standards have recently emerged. Ultimately, if these aspirational standards are to have their desired benefits, they realistically must achieve operationalization while not impeding development of the nascent sector. This Chapter will discuss how existing agricultural conservation programs in the U.S. can aptly inform these efforts.

Introduction

Biomass-based energy is facing mounting scrutiny of whether it truly achieves the environmental and social sustainability fitting for some of a "renewable" fuel. The loudest biofuels skeptics, such as Searchinger et al. (*1*), argue that as biofuels mandates like the Renewable Fuel Standard in the U.S. create competition for land resources, the global market price for agricultural commodities necessarily

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rises and as a result, farmers in Country B (e.g. Brazil) are induced economically to clear native forests that otherwise serve as valuable carbon sinks. Thus, the argument follows that greenhouse gas (GHG) policies must take these "indirect land use changes" into account in lifecycle analysis of biofuel emissions. Others (*2*) contend that higher commodity prices, caused at least in part by higher demand for biomass, also create food insecurity in countries particularly vulnerable to price shocks. Lastly, if biomass cropping is heavily dependent on water and inputs, Angelo (*3*) argues that "renewable" biomass merely maintains an unsustainable status quo within commodity agriculture.

These developments highlight the relevance of considering standards for energy biomass to remedy these perceived and real shortcomings. Governments, to various degrees, have responded by incorporing sustainability considerations in biomass-based energy policy. The Obama Administration (*4*) has emphasized that federal agencies must take a new "integrated approach" to achieving renewable energy targets, with an emphasis on conducting an "upfront" assessments of sustainability in biomass feedstock production systems. The Environmental Protection Agency (EPA) (*5*) issued only recently its first Triennial Report on the environmental effects of the Renewable Fuel Standard (RFS). Among states, California leads in developing a comprehensive GHG regulatory program (*6*) that directly implicates the sustainability of biomass feedstocks. Abroad, the European Union's Renewable Energy Directive (RED) (*7*) requires sustainability certification to qualify toward the ten percent renewables mandate in transportion fuels by 2020. In light of these and other policies, and in anticipation of compliance and environmental services markets, private standards such as the Roundtable for Sustainable Biofuels (RSB) (*8*) and the Council on Sustainable Biomass Production (CSBP) (*9*) have emerged.

This Chapter addresses the ability of private standards such as these to address the mounting criticisms of biofuels environmental and social impacts. In particular, the Chapter focuses on whether existing frameworks for agricultural sustainaibility in the U.S. could be used by producers seeking certification to achieve the greater sustainability driven by private sustainability standards for biomass. It first presents a general overview of the evolution of biomass sustainability requirements in the U.S., followed by an in-depth discussion of how the conservation planning and practices of the Natural Resources Conservation Service (NRCS) could serve as at least a starting point for operationalizing biomass sustainability standards. Next, the Chapter contemplates whether current U.S. agro-environmental programs, which use scorecards as a basis for funding projects, could be borrowed from in operationalizing biomass standards. Lastly, the Chapter will conclude with a discussion of how U.S. bioenergy policy could move toward a more credible, feasible, and consistent measure of biomass sustainability.

The Evolution of Biomass Sustainability Requirements

Although specific definitions can vary particularly if based in legislation, "sustainable" or "renewable energy" sources generally are those which neither can be depleted substantially by continual use, nor emit significant amounts of pollution (*10*). Just like the wind that blows, the sun that shines, and rivers that flow, plants can regenerate and thus are arguably renewable. This is not to say, however, that energy biomass cannot have detrimental environmental and social effects. For example, conventional agriculture relies on petrochemical inputs, mechanization, and vast stretches of monocultures that can deplete soil, water and habitat quality. Some argue, therefore, that energy feedstocks deriving from this type of system cannot be deemed “sustainable,” “renewable,” “green,” “alternative,” etc.

No single consensus exists on exactly what constitutes a truly sustainable agricultural system. Turner (*11*) has posited that sustainable systems “supply a growing population with [X commodity, be it food or energy] without destroying the environment within which it is [derived] and used, providing [X commodity] for the present without compromising the ability of future generations to meet their needs.” Harwood (*12*) provides a more human-centric definition, contending that agricultural systems are sustainable when they “can evolve indefinitely toward greater human utility, greater efficiency of resource use, and a balance with the environment that is favorable both to human and to most other species.” Energy biomass, too, has entered the sustainability debate, as groups such CSBP (*9*) are beginning to broadly define sustainability to address not only agronomics, but also social consequences (e.g., food security, labor standards, and community development).

Just as definitions of sustainability vary (*10–12*), no consensus currently exists on how to *achieve* a sustainable agricultural system. Chappell and La Valle (*13*) have concluded that various “alternative” agricultural practices (e.g., integrated pest management, no-till, and closed-loop plant nutrient systems) can lead to increased environmental quality, larger profits for small farmers, and global food security. On the other hand, others including Muller (*14*) has argued that because widespread adoption of alternative practices will lead to decreased yields and elevated costs, the system should depend on gaining yields through genetically-modified plants on the same or fewer amount of acres. Chappell and La Valle (*13*) counter that such a strategy results in economic pressures that lead to deforestation for cropping. With these disparate views in mind, I now turn to how U.S. bioenergy policies define “renewable biomass.”

The Varying Definitions of “Renewable Biomass” in U.S. Law

Despite the environmental damage caused by corn production (including Gulf of Mexico hypoxia as reported by Costello et al. (*15*)), U.S. biofuels production has historically relied on it as a primarly feedstock. The Energy Independence and Security Act of 2007 (EISA) (*16*) (also known as the Renewable Fuel Standard) ushered in, for the first time at least in formal legislation, the premise that “renewability” should have some type of meaning other than merely regenation of a crop. The next year, the 2008 Farm Bill included conservation planning as a condition for a subsidy payment (*17*). And, only recently has the California Air Resources Board proposed principles, criteria and indicators of sustainability for fuels qualifying for its Low Carbon Fuel Standard (*18*).

The Renewable Fuel Standard

The Renewable Fuel Standard (RFS2) (*16*) mandates blending of increasing amounts of advanced biofuels, cellulosic biofuels, biomass-based diesel, and “renewable” fuels in the U.S. fuel supply through 2022. Each of these fuel categories of must achieve a certain amount of greenhouse gas (GHG) emission reduction, and feedstocks must qualify as “renewable biomass” (*16*). The RFS2 contains categories of inclusion (e.g., cropped and forest materials and residues, algae, and yard, food and animal waste), and excepts out certain materials. Requirements (*16*) focus mainly on land conversion restriction in order to protect fragile native grasslands and forests from increased demand for biomass acres. Blenders therefore must demonstrate that feedstocks do not derive from lands cleared after December 2007 (*16*). The act (*16*) also limits biomass sourcing from non-federal forests and completely disqualifies materials from public lands. On private lands, residual harvests cannot dervice from late succession forests, old growth forests, and forests with ecological communities of certain global or state ranking (*16*).

The U.S. Environmental Protection Agency (EPA), the agency with jurisdiction over RFS2, is taking an “aggregate compliance” to enforcing land conversion restrictions ((*19*) at 14681). Under this scheme, biomass producers do not need to retain any records of compliance unless the “2007 baseline” amount of agricultural land (measured by the U.S. Department of Agriculture (USDA)) has been exceeded (*19*). For other RFS2 sustainabilty requirements related to sourcing, producers either must keep records and report, or fund an independent third-party entity to conduct a “survey” for “quality assurance” (*19*). Environmental groups are challenging, among other provisions of EPA’s implementing rules for the RFS2, this aggregate compliance approach (*20*).

Although RFS2’s sustainability related provisions focus primarily on land-use change, EISA also requires EPA to report periodically on the range of other detrimental environmental effects biofuels could have, such as air, water and soil quality, and ecoysystem health and biodiversity (*16*). EPA broadly surveyed these potential effects in its first triennial assessment in 2011 and indicated therein that it will use lifecycle analysis (LCA) for future reporting efforts (*5*). However, the limitations of LCA in dealing with complex systems, and the paucity of data particularly for second-generation crops, likely will make any such attempt extremely difficult.

The Biomass Crop Assistance Program (BCAP)

BCAP (*21*), the first subsidy program for energy biomass cropping in the U.S., consists of two parts: projects area payments for establishment and growing of perennial woody and cropped biomass; and, matching payments for its collection, harvest, storage and transportation. The Commodity Credit Corporation (CCC) and Farm Services Administration (FSA), within the USDA, are responsible for BCAP implementation. For payment under either, biomass must qualify as “renewable biomass” (*21*). BCAP and RFS2 share some commonalities and differences in this regard. For example, BCAP similarly establishes categories of renewable biomass, such as cropped and forest materials and residues, and non-yard waste grasses and vines (*21*). Algae and animal wastes, however, are excluded (*21*). BCAP-subsidized biomass cannot be harvested from Conservation, Wetland, or Grassland Reserve lands, but unlike the RFS2, biomass from federal lands are not blanketly excluded (*21*). A land conversion prohibition by date (October 2010) applies, and Title I crops (first generation biofuels feedstocks that receive general federal subsidies, such as corn and soy) do not qualify for BCAP payments (*21*).

In addition to categorical qualifications, "renewable biomass" must observe wetland and highly erodible lands protections, and be produced according to an approved conservation or forest stewardship plan, or the equivalent (*22*). Implementing regulations (*22*) define conservation planning as "a record of the participant's decisions and supporting information for treatment of a unit of land or water, and includes a schedule of operations, activities, and estimated expenditures needed to solve indentified natural resource problems by devoting eligible land to permanent vegetative cover, trees, water, or other comparable measures." More specifically, BCAP regulation (*22*) defines planning as that required under the Conservation Reserve Program (the agricultural subsidy program that idles ecologically vulnerable areas) (*22*). The USDA's Natural Resources Conservation Service (NRCS) develops conservation plans for CRP land (*23*), and thus would also be responsible for those developed for BCAP. State foresters, under a program established by the U.S. Secretary of Agriculture, develop forest stewardship plans (*24*). In addition to conservation plans in place, it appears that FSA is requiring full environmental assessments as a condition of project area approval (*23*), although such assessments are not specifically required in implementing regulations (*25*).

California's Comprehensive GHG Regulatory Program

The enactment of California's Global Warming Solutions Act of 2006 (*6*) has generated several sector-specific regulations such as Renewable Electricity Standards (*27*), a Low Carbon Fuel Standard (LCFS) (*28*), light-duty vehicle emission limitations (*29*), and a cap-and-trade regulation for major stationary sources (*30*). Around the time the Act was passed, the California Biomass Collaborative prepared a Biomass Roadmap (*31*) for the California Energy Commission (CEC) that emphasized the need to consider the sustainability aspects of biomass feedstocks. The California Air Resources Board (ARB) currently is in the process of considering sustainability metrics for energy biomass feedstocks for the LCFS (*32*), with the goal of finalizing provisions by December 2011 (*33*). ARB's LCFS Sustainability Work Group has recognized the importance of examining existing agro-environmental programs to determine their efficacy in achieving sustainability. Likewise, the Interagency Forestry Working Group (*34*) also is developing similar sustainability standards for forest biomass. The CEC applies sustainability metrics to renewable energy projects funded under Assembly Bill 118 (*35*).

Certification to a Standard as a Proxy for Sustainability

As seen in the RFS2, BCAP and California's regulations, biofuels policy is trending toward establishing some type of sustainability requirements for biomass feedstocks. Endres (*36*) has posited that one way to ensure credibility of sustainability requirements is through certification. As defined by Rametsteiner and Simula (*37*), certification is "the process whereby an independent third-party (called a certifier or certification body) assesses the quality of [agronomic] management in relation to a set of predetermined requirements (the standard)." Lewandowski and Faaij (*38*) have noted that *standards* "define the aim of certification, and describe the product or production process specific requirements to be fulfilled by certification", *principle* statements establish the standard's general aspirations by category, *criteria* describe in further detail the principle-specific requirements, and *indicators* provide the details required for measurement. Sikdar has added (*39*) that criteria and indicators can either be performance based or prescriptive.

Lewandowski and Faaij have further reported (*38*) that, beginning in the 1990s, the organic food sector was the first to develop a system of certification based on a set of standards, followed shortly thereafter by the forestry sector. They further noted (*38*) that sustainability standards for other types of agriculture have been slower to develop, particularly in the U.S. While the European Union's Common Agricultural Policy (*40*) has required environmental cross-compliance from agricultural commodity producers since 2003, and requires the same in its Renewable Energy Directive (*7*), U.S. agricultural producers remain subject to very few mandatory conservation measures.

Endres has theorized (*36*) that the advent of renewable energy policy in the U.S. in the past years has resulted in a renewed dialogue about the sustainability of agriculture beyond organic agriculture. She noted (*26*) that emerging standards for biomass cropping are generally performance-based and rely on management practices to achieve environmental goals such as improving soil, water and air quality, and enhancing biodiversity. Most standards typically start with a principle related to management planning that, in turn, guides each successive principle. Other environmental principles directly relate to water, air, soil, and biodiversity protection. Because priorities and perceptions between stakeholders may vary significantly (e.g., industry and trade, buyers and consumers, producers and managers, governments and academic representatives, environmental and labor non-governmental organizations), development of private biomass sustainability standards wisely has involved a variety of stakeholders.

The Provisional Standard of the Council on Sustainable Biomass Production

Fuchs has reported (*41*) that standards development for the global agricultural production system, including for energy biomass, is becoming increasingly populated by private actors. This is most likely in response to certification requirements under the European Union's Renewable Energy Directive (RED) (*7*) that became effective December 2010, as well as speculation that other countires like the U.S. will require some type of traceability in the future. For example, the Roundtable for Sustainable Biofuels (*8*), a private, transnational, multi-stakeholder group has developed a RED-compliant standard. In the U.S., the Council on Sustainable Biomass Production's (CSBP) multi-stakeholder effort among industry, biomass producers, academics, and non-governmental organizations led to issuance of a provisional standard for biomass (*9*) in April 2010. The CSBP is completing field-testing, with a final standard expected to be completed by 2012.

The CSBP provisional standard (*9*) contains nine main principles, which include integrated resource management planning, soil, biological diversity, water, climate change, socio-economic well-being, legality, transparency, and continuous improvement. Each principle contains (*9*) criteria and indicators, as well as implementation guidance. Furthermore, the standard (*9*) has set a two-tiered compliance system consisting of silver and gold levels. Where necessary, the standard (*9*) will set metrics, but it recognizes that gauging performance through management practices might be less costly than testing and implementing metrics. Many of the standard's provisions are addressed (at least in part) by NRCS practice standards.

Operationalization of Biomass Sustainability Standards through Natural Resources Conservation Service Planning and Practices

Despite progress made by private standards like the CSBP toward building a standards framework, Dale et al. (*42*) have reported "there is not yet a firm consensus on the extent of [the potential impacts of biofuels production on land use and biodiversity] and how to measure them." Standards, therefore, should give consideration to whether existing agro-environmental programs can provide a template for further operationalization. These programs could potentially provide guidance for designing baseline resource assessment and planning, and tools for execution of both practices and measurement of their results. In the U.S., NRCS (along with the Farm Service Administration and state Conservation Districts) plays a central role in assisting producers with the conservation requirements of commodity subsidy programs and other conservation programs like the Conservation Reserve Program. Bioenergy policies such as BCAP refer to NRCS conservation planning as one way to qualify "renewable biomass" for a subsidy. NRCS provisions, therefore, likely will play an important part the implementation of biomass sustainability standards.

NRCS's strategy for conservation is based on, in addition to foundational laws and regulations (which are not detailed in this chapter), policies (i.e., general manuals), procedures (i.e., handbooks), technical guidance, tools, and program guidance (i.e., manuals). General manuals provide the foundational, over-arching guidance for NRCS's conservation planning and practices. Manuals establish guidance and policy aimed at implementation of specific federal programs (e.g., the Environmental Quality Incentives Program (EQIP) (*43*) and the Conservation Stewardship Program (CSP) (*44*)). One of the most significant manuals, in terms of future development of biomass cropping practices, could be the National Agronomy Manual (NAM) (*45*). University and industry research is still in the nascent stage, however, of developing recipes for successful biomass production and determining environmental benefits and tradeoffs. NRCS also issues handbooks that further detail procedures for field office staff to use in implementing conservation practices and policies. Of these handbooks, the National Planning and Procedures Handbook (NPPH) (*46*) and the National Handbook of Conservation Practices (NHCP) (*48*) are of particular relevance to operationalizing biomass sustainability standards.

At the field level, the NRCS Field Office Technical Guidance (FOTG) (*49*) directs the planning process and implementation of conservation practices. While it serves as a primary scientific reference for NRCS, the FOTG (*49*) also contains county-level resource targets and practices to achieve those targets. Each state has its own FOTG that is approved by its State Conservationist, containing: (1) general resource references (e.g., links to manuals and handbooks, modeling tools, maps, watershed information, and agricultural laws and regulations); (2) natural resources information (e.g., detailed information on soil, water, air, plant, and animal resources, as well as soil surveys, wildlife habitat evaluation guides, water quality guides, and cropland production tables); (3) conservation management systems (i.e., the resource concerns and accompanying quality criteria); (4) practice standards and specifications (i.e., detailed requirements for installing the practice in the particular state); and (5) conservation effects (i.e., how the conservation practice affects each identified resource concern in the state). In some cases, producers will contract with Technical Service Providers (TSPs) to assist in implementing conservation practices (*50*).

The Conservation Planning and Practices Framework of NRCS

NRCS tailors its services to each producer's individual goals, with the process usually being dictated by the federal program for which the producer seeks payment. Regardless of the individual's situation, NRCS follows a general framework to identify "resource concerns" and to design conservation plans and practices. The conservation practice chosen depends on the resource concern at issue and the corresponding NRCS quality criteria.

Identifying Resource Concern(s)

Various federal statutes charge NRCS with the task of continuously assessing the needs and status of water, soil, and other related natural resources in the U.S. The primary mechanism that NRCS uses for gathering this information is the National Resource Inventory (NRI) (*51*). The NRI (*51*) relies on statistical surveys of site-specific sample data gathered through NRCS onsite visits, remote sensing, imagery, and "ancillary materials" containing data. NRCS coordinates the NRI (*51*) with other government resource assessments "when feasible, practical, and consistent with NRCS' conservation mission." The NRI (*51*) is conducted on an annual basis to assess: (1) land use; (2) the landscape and soil; (3) ecological site information; (4) rangeland health; (5) invasive/noxious plant presence; (6)

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disturbance indicators; (7) conservation practices and resource concerns; (8) plant composition and patterns; and (9) plant production, cover, density, and height. The problems that NRCS identifies in an NRI (*51*) are referred to as "resource concerns" and form the building blocks of quality criteria in conservation planning and management. These resource concerns are categorized by the areas in which they can occur: soil, water, air, plant and animal ("SWAPA"). Additionally, NRCS has also added human resources ("H") and energy ("E") to the SWAPA framework.

Conservation Management Practices and Quality Criteria

NRCS' National Agronomy Manual (NAM) (*45*) provides a general reference for its conservation practices, defined as "a specific treatment, such as a structural or vegetative measure, or management technique, commonly used to meet specific needs in planning and implementing conservation for which [quality] standards and specifications have been developed." The NAM (*45*) includes chapters that detail water and wind erosion, the tools that measure them, and their relevant control measures. In addition, other chapters address (*45*) cropping practices (e.g., crop rotation, tillage, and residues), water management (e.g., soil moisture), plant attributes (e.g., vegetative stabilization and suitability for crop production systems), cropland conservation management systems, soils (e.g., surveys, interpretation, and management), and data management.

While the NAM is more general in nature, the National Handbook of Conservation Practices (NHCP) (*47*) specifically sets conservation practices and minimum quality criteria for each resource concern and outlines "why and where the [conservation] practice is applied" to meet the quality criteria. Each conservation practice is broken down into its separate practices (*47*), ranging from "brush management" to "windbreak/shelterbelt renovation". NRCS incorporates modeling tools (e.g., the Soil Conditioning Index (SCI)) in order to measure individual effectiveness within these specific practices. Finally, these cornerstone practices and quality criteria are tailored to state-specific conditions within the state-specific FOTGs (*49*).

For specific issues where no practice standard exists, the NHCP (*48*) establishes procedures for developing an interim standard. These procedures include interfacing with agricultural producers, industry representatives, NRCS field office personnel, and researchers from universities and the Agricultural Research Service. As many conservation practices and effects only are beginning to be understood, these procedures for interim development of practices and quality criteria could be used to build standardized practices and quality criteria for energy biomass cropping,

NRCS Conservation Planning

The ultimate goal of NRCS's conservation planning is to provide producers with a framework to implement the conservation management practices detailed above. As outlined in the National Planning and Procedures Handbook (NPPH)

(*46*), this process holistically centers on the development of a "Resource Management System" (RMS). Through the RMS, NRCS aims to establish producer practices and activities that meet or exceed its quality criteria. While the RMS is set as a minimum goal, NRCS allows (*46*) producers who are not "ready, willing and able" to meet all criteria to "progressively" plan.

The NPPH (*46*) primarily guides the NRCS planning process, which NRCS coordinates within a multi-tiered structure. At the broadest level, area-wide conservation plans and assessments guide actions at a watershed or larger geographic level. These area-wide assessments encompass individual operations, "land units" within those operations, and sub-units (*46*). The entire individual planning process covers three phases and a total of nine steps (*46*). The result is a conservation plan, which NRCS has described (*46*) as being "voluntary, site-specific, comprehensive, and action oriented". As further described in the General Manual (*47*):

> A conservation plan contains natural resource information and a record of decisions made by the client. It describes the schedule of operations and activities needed to solve identified natural resource problems and take advantage of opportunities. Using the planning process to develop conservation plans helps ensure that the needs of the client and the resources will be met, and that federal, state, and local requirements will be achieved.

At phase one of the process (*46*), the producer identifies resource problems/conditions, identifies production objectives, and analyzes existing information about the resources at issue. In addition, Local Conservation District preferences and resources also are identified. The NPPH (*46*) identifies resource problems or conditions, including those related to: (1) soil quality and quantity (e.g., erosion, condition, deposition); (2) surface and ground water quality and quantity; (3) air quality; (4) plant-specific conditions (e.g., diversity loss, noxious or invasive weeds, endangered species, pest infestation, and deforestation); (5) animals (e.g., wetland and other habitat quality); and (6) human social and economic conditions.

Based on this initial assessment, the producer is directed (*46*) to then formulate, evaluate, and choose from alternative actions to remedy its resource problems. The NPPH recommends (*46*) alternatives that span:

> [a] broad range of technically feasible alternatives . . . including an appropriate mix of structural measures . . . non-structural measures such as crop residue management, livestock exclusion, and flood-proofing; market-based measures such as cost-sharing, easements, and local tax incentives; and institutional measures such as zoning or local regulations, and state and federal laws and regulations.

Plans must evaluate (*46*) alternative practices not in isolation, but instead must be "aware of the effects on all resources". The final phase concludes with plan implementation and evaluation where the producer provides important feedback so that the producer and NRCS can adjust quality criteria and/or practices.

Models and Other Tools for Estimating the Sustainability of Biomass Cropping

A wide variety of tools are available to assist producers in determining whether their practices meet the NRCS quality criteria for a given resource concern. Direct measurement tools and predictive models can estimate the environmental effects of agricultural practices on soil, water and air, which in turn informs alternative choices in the planning process. In addition to measuring impacts at the farm level, models and assessment tools also are capable of gauging more macro-level impacts–for example, in a watershed.

This Chapter does not attempt to discuss all available tools, as there are many unique ones in existence and development worldwide. Instead, the following discussion centers on tools currently used to assess soil and water impacts within the context of NRCS conservation planning. It is these that hold the most potential for use in conservation planning for energy biomass in the U.S., although the scientific community must work to close gaps in biomass-specific knowledge.

Biomass Cropping Impacts on Soils

As noted in USDA's Soil Survey Manual (SSM) (*52*), soil surveys provide the fundamental understanding of soil properties necessary for conservation planning that achieves improvements in not only soil quality, but water, air and habitats as well. A soil survey "describes the characteristics of the soils in a given area, classifies the soils according to a standard system of classification, plots the boundaries of the soils on a map, and makes predictions about the behavior of soils" (*52*). The principles and practices that soil scientists use on the ground in classifying and mapping soils are detailed in the SSM (*52*). Furthermore, the SSM describes (*52*) how a soil survey can provide producers information regarding differences in soils and environmental factors that influence their use, management and behavior (e.g., soil type/taxonomy, structure, productivity, erosion, drainage/infiltration, temperature, animal presence, and chemical properties such as pH and salinity).

NRCS has identified (*53*) soil condition (e.g., organic matter content, soil compaction, and contaminants) and soil erosion as primary resource concerns. Both national and state quality criteria exist for each of these concerns. These criteria may require a certain score on a soils modeling tool, the application of specific management practices (e.g., controlling runoff and monitoring chemical and fertilizer application), and/or following NRCS guidance specific to a given practice.

As indicated in the NAM (*45*), the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) is NRCS's official modeling tool for predicting soil loss due to water erosion. RUSLE2 (*54*) currently exists as a downloadable computer program that allows its user to estimate the average annual soil loss resulting from erosion on a given piece of land. In general terms, RUSLE2 estimates annual soil loss based on a consideration of "climate, soil properties, topography, vegetative cover, and conservation practices" (*54*). The current version of RUSLE2 (*54*) utilizes a graphical user interface and accompanying databases that contain baselines, climate and soils data, and crop management templates.

The average annual soil loss predicted by RUSLE2 (*45*) is used in two distinct ways for conservation planning purposes. First, RUSLE2 can be used to generate alternate cropping scenarios that can be compared against each other to advise conservation planning decisions (*45*). Second, it also can be used to compare the outputted average annual soil loss to the predetermined soil loss tolerance value (usually referred to as "T") in order to determine if existing farming practices can meet a given level of conservation (*45*). If the average annual soil loss generated by the RUSLE2 Program for a given field is equal to or less than the relevant T value, then the landowner is considered to be utilizing its soil in a sustainable manner (*45*). If the landowner's average annual soil loss is greater than the relevant T value, then the landowner is directed to utilize RUSLE2 to determine what alternative farming practices might be implemented to produce an average annual soil loss that is less than or equal to the relevant T value (*45*).

For purposes of assessing soil condition (versus erosivity), the NAM (*45*) emphasizes the use of the Soil Conditioning Index (SCI). The SCI measures soil organic matter (SOM), which NRCS has defined (*55*) to include "living biomass of microorganisms, fresh and partially decomposed residues, and well-decomposed and highly stable organic matter." Because increased SOM boosts soil productivity, cycles nutrients, and buffers against water pollution, it is considered to be one indicator of sustainable practices (*56*). SOM also encourages cation exchange, soil stability, soil biological activity, and the ability of soil to hold water (*45*).

As different management practices can negatively affect SOM (e.g., excess erosion leads to loss of valuable soil nutrients, particles and matter and certain tillage practices can result in accelerated organic matter decay), the NAM (*45*) provides a description of how producers can input their operation's practices into the SCI tool during the planning process in order to determine whether the practices will lead to increased, decreased or maintained SOM. The SCI qualitatively measures biomass cycled through the soil (whether from within or outside the farm gate), the effects of tillage and inputs, and erosion. The model assumes that equilibrium is only achieved if biomass is returned to the soil at the same rate it decays (*45*). As rate of decay depends in part on moisture and temperature differences throughout the U.S., NRCS incorporates these differences into the model's databases (*45*).

In addition to calculating erosivity, RUSLE2 will generate an SCI value. If the value is zero or positive, the user is considered (*45*) to be managing its SOM content in a sustainable manner, whereas if the value is negative the producer (*45*) is not managing SOM content for maximum productivity. Essentially, the user creates alternate runs of RUSLE2 with varying inputs to determine which scenario might result in a positive SCI value. Based on these alternate runs, the user can then formulate a conservation plan that will potentially result in the sustainable maintenance of SOM content.

Biomass Cropping Impacts on Water Quality

NRCS maintains a National Water Quality Handbook (NWQH) (*57*) to guide personnel in assessing and monitoring water quality concerns, incorporating management practices into producer conservation plans, and implementing practices that address agricultural non-point sources of pollution. NRCS, in conjunction with local and state authorities, monitors program participants practices and water body pollution characteristics (*57*) to analyze both trends in water quality and to isolate pollutant sources. NRCS then takes this information (*57*) and devises Resource Management Systems where water pollution is of greatest concern. NRCS' water quality monitoring (*57*) ensures compliance with programmatic conservation requirements, allocates conservation practices within a watershed, and evaluates program effectiveness.

In order to gauge the effectiveness of various agricultural conservation practices to reduce non-point source pollution in large and complex watersheds, Gassman et al. have reported (*58*) that the USDA currently uses the Soil and Water Assessment Tool (SWAT). They have further explained (*58*) that SWAT contains many modules that simulate cropping and management practices on different soils and their effects on water quality, sediment, and "chemical yields." Gassman et al. (*58*) have used the model to evaluate best management practices related to pollutant losses from such practices as "fertilizer and manure application rate and timing, cover crops (perennial grasses), filter strips, conservation tillage, irrigation management, flood-prevention structures, grassed waterways, and wetlands." Despite the fact that the model is not used at the individual producer level, the model can be useful to policymakers designing sustainability regimes for biomass to the extent that it can simulate energy biomass cropping practices in aggregate within a watershed.

Finally, Gassman et al. have noted elsewhere (*59*) that the Agricultural Policy Environmental EXtender (APEX) model, embedded in SWAT, calculates agricultural management practices at smaller scales. They predicted (*59*) that APEX modeling will provide "multi-subarea capabilities" in the future to evaluate "different cropping systems and conservation practices on varied landscapes". In the end, valuing complex aquatic systems through modeling will perhaps demonstrate the net benefits of energy biomass cropping within any sustainability standard, government compliance regime, or in emerging water services markets.

Biomass Cropping Impacts on GHG Emissions and Biodiversity

The Carbon Management Online Tool for Voluntary Reporting (COMET-VR) estimates the amount of carbon that is stored or sequestered in soil, depending on land use practices (*60*). Currently, COMET-VR is the official tool for estimating soil carbon sequestration for both the Department of Energy's (DOE) Voluntary Reporting of Greenhouse Gases Program (*61*) and USDA's Conservation Stewardship Program CSP (*62*). COMET-VR provides landowners an online tool to determine their soil's annual carbon flux based on simulations created by the CENTURY model. The CENTURY model, also developed and maintained

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ACS Symposium Series; American Chemical Society: Washington, DC, 2012.

by Colorado State and the National Renewable Energy Laboratory, generally simulates SOM dynamics in relation to management practices and climate within different types of ecosystems including grasslands, agricultural lands, forests and savannas (*63*). CENTURY utilizes several unique modules, including those for soil organic matter/decomposition and water budgeting, plus ones unique to grassland/crops and forest production (*58*). CENTURY can compute sulfur, phosphorus, nitrogen, and carbon fluxes within each module (*58*). To operate the model, producers must input their land characteristics into COMET-VR, including the location, type and size of the operation, surface soil texture, and whether or not their soil is hydric (*58*). After the user inputs all of this information, COMET-VR generates a "Carbon Storage Report" that predicts the change in soil carbon for the given parcel (expressed as total tons of carbon stored per year and total tons of CO2 equivalent per year stored) (*58*). The model also calculates the average diesel fuel used for tillage and nitrogen use for both the current management and Report periods (*58*). For conservation planning purposes, COMET-VR is used in a manner similar to RUSLE2, although it is not yet integrated into the suite of NRCS online tools.

As for biodiversity tools, NRCS' National Biodiversity Handbook (NBH) (*64*) describes various fish and wildlife habitats and devises ways, through the National Conservation Partnership, in which to incorporate biodiversity considerations into conservation management planning. While the NBH recognizes the value of perennial grasses in corridors and buffer strips, it does not elaborate on the role of larger-scale energy biomass cropping in biodiversity enhancement. NRCS's Agricultural Wildlife Conservation Center (AWCC) (*65*), founded in 2006 to research habitat needs on agricultural lands and develop conservation technologies, was closed in March 2011. It is unclear what efforts, if any, will take its place.

Agro-Environmental Subsidy Programs as a Scorecard for Biomass Sustainability

Feng et al. have posited (*66*) that generally the retirement of lands for conservation purposes, and incentives to change existing agricultural practices, have been the two dominant U.S. policy options for increased environmental sustainability in agriculture. They also noted (*62*) that over the past three decades, the majority of federal funding has gone toward land set-aside programs. However, beginning with the 2002 Farm Bill, they note (*62*) that the policy has shifted to achieving sustainability while keeping land in agricultural production. Despite the fact that keeping lands productive be more cost effective, Feng et al. have concluded (*62*) that researchers are only beginning to explore the environmental tradeoffs between idling land for conservation and conservation through management practices.

In addition to receiving BCAP payments (*17*), which subsidize the production of energy biomass where conservation plans are in place, energy biomass producers may receive additional federal assistance by participating in "working lands" environmental enhancement programs such as the Conservation

Stewardship Program (CSP) (*44*), the Environmental Quality Incentives Program (EQIP) (*43*), and the Wildlife Habitat Improvement Program (WHIP) (*67*). Likewise, the Conservation Reserve Program (CRP) (*68*) also contains a mechanism for evaluating the potential environmental benefits of idling agricultural land while accommodating a certain level of biomass harvests. These programs conceivably provide policymakers an option for "grading" biomass sustainability because they contain assessment mechanisms and indicators that could initially provide a stand-alone sustainability framework while economic and scientific research more fully grasps the environmental benefits (and perhaps harms) of energy biomass cropping. Furthermore, sustainability metrics within these existing agro-environmental programs could inform individual criteria and metrics development for NRCS or in emerging biomass-specific sustainability standards.

The Conservation Stewardship Program

The Conservation Stewardship Program (CSP) (*44*) provides funding through 2012 for producers to both improve existing, and incorporate new, conservation practices into their operations. The majority of a participating operation's land must be in a watershed (*44*). Monies are available nationwide through continuous sign-up periods in which NRCS ranks proposals through a point-scoring process where the top-ranked projects receive CSP funding (*44*). Producers cannot receive CSP payments for services already reimbursed under the Conservation, Grassland, or Wetlands Reserve Programs, or for newly converted land except under certain circumstances (*44*).

For purposes of the CSP (*44*), project proposals compete on additionality, which means that in order to qualify for payment, producers must meet a "stewardship threshold" for one "resource concern" at the time of contract, maintain those practices to support that threshold, and meet or exceed an additional priority stewardship threshold for one additional resource concern by the end of the five-year contract period. A "stewardship threshold" is defined (*44*) as the level of management necessary to "conserve and improve the quality and condition of a natural resource". State Conservationists are directed (*44*) to consult with the State Technical Committee and local working groups to identify priority resource concerns for a State, or a specific geographic area within the state, that relate to water quality and quantity, soil quality, air quality, and wildlife habitat. If eligible, a producer can receive payment for costs incurred, foregone income, and the environmental benefits provided (*44*). Producers can receive supplemental payments for resource-conserving crop rotation, as well as participation in on-farm research, demonstration, and pilot testing (*44*).

As mandated by the CSP's implementing regulations (*69*), the state conservationist (or a designate) must rank project applications using the Conservation Measurement Tool (CMT). The CMT determines a project's "conservation performance" using a point system that measures relative physical effects instead of "true" environmental benefits (*69*). During the first sign-up period in 2009, NRCS and a panel of experts developed a set of questions to evaluate existing practices and to score practices that would lead to additional enhancements (*69*). Pursuant to regulation (*69*), project applications are to be ranked on the following five factors: (1) the level of "conservation treatment" on all applicable priority resource concerns at the time of application; (2) the degree to which the proposal increases performance related to those priority resource concerns; (3) the number of priority resource concerns that the applicant proposes to be treated in order to meet or exceed the stewardship threshold; (4) additional resource concerns that will be treated to meet or exceed the stewardship threshold; and (5) where a tie-breaker is necessary, the extent to which the project represents the least cost to the program. As a condition of receiving CSP funding (*69*), producers must implement a conservation stewardship plan that follows the general NPPH process discussed above. Where new technology exists that "ha[s] a high potential for optimizing environmental benefits" (which is very likely in an energy biomass production scenario), NRCS will approve a CSP payment for the practice until a practice standard can be developed (*70*).

The Environmental Quality Incentives Program

When a producer does not reach the threshold requirements for the CSP program, monies nonetheless may be available through the Environmental Quality Incentives Program (EQIP) (*43*). Congress created the program in 1996 as an incentive for agricultural and forest producers to provide increased environmental benefits through NRCS technical assistance and direct financial payments. NRCS administers EQIP through State Conservationists. The program is based on national resource priorities that include reduction in soil erosion, air pollution, and non-point source water pollution, and habitat conservation for "at-risk species" (*43*). Producers incorporate these goals into conservation management planning and implementation, with goals enforced through contracts with a maximum duration of 10 years (*43*). Congress has mandated (*43*) that forty percent of EQIP funding is available for non-livestock related practices and payments may not exceed $300,000 per entity. As outlined in NRCS's General Manual (*47*), program applicants are scored using the Application and Evaluation Ranking Tool (AERT). Projects receive funding based on State Conservationist rankings of: (1) cost-effectiveness; (2) the magnitude and longevity of environmental benefits; (3) compliance with all applicable laws; (4) timeliness in implementing the practices; and (5) improvement of existing conservation practices.

The Wildlife Habitat Incentives Program

Congress created the Wildlife Habitat Incentives Program (WHIP) (*67*) to assist agricultural producers, through a cost-share program valued at up to $50,000 per year per producer, in creating habitat for upland and wetland wildlife, endangered and threatened species, and fish. WHIP's implementing regulations (*71*) charge the State Conservationist, in consultation with the State Technical Committee, with implementing the program. NRCS is permitted to set species and geographical priorities each year and can enter into agreements with private conservation groups and local agencies to implement the program (*71*). The regulations (*71*) provide that "general" WHIP funding (up to 75% of the cost of installing the conservation practice(s)) is available for projects lasting between 5 and 10 years that develop habitat. Funding for longer term projects (up to 90% cost-share for up to 15 years) is available for projects that protect and restore plant and habitat (*71*).

WHIP's implementing regulations (*71*) direct NRCS to select projects by ranking them according to: (1) whether they address an identified local, state or national habitat problem; (2) their relationship to a established conservation or wildlife areas; (3) the expected length of benefits proposed by the project; (4) whether the project can be self-sustaining; (5) the availability of matching funding; (6) the estimated cost of the project; and (7) any other appropriate factors determined by NRCS. Furthermore, this ranking process identifies both state-specific issues and national issues. If chosen, the regulations (*71*) require participants to develop a wildlife habitat development plan, part of which is accomplished through the general NRCS planning process outlined above.

The Conservation Reserve Program

The Conservation Reserve Program (CRP) (*68*) was created in the 1985 Farm Bill and is now the largest conservation program in the U.S. by acreage and expenditures. The Program aims to "conserve and improve soil, water and wildlife resources", and Congress has expressed a desire that the three be equitably balanced (*68*). Land eligible for the program includes certain marginal pasture land converted to wetlands or wildlife habitat, marginal pasture land devoted to water quality uses, highly erodible land, and other types of land that are otherwise ineligible that would provide environmental benefits (*68*). Congress (*68*) has capped the total number of eligible acres at 32 million between 2010 and 2012, and pursuant to regulations (*72*), no more than 33% of land within any state can be CRP land. CRP contracts, which last from 10 – 15 years, pay an annual rent and half the cost of establishing permanent land cover (*68*). CRP regulations (*72*) provide that NRCS can designate priority areas for funding if significant adverse air, water, wildlife, or other resource issues related to agriculture exist.

As Ribaudo has noted (*73*), the CRP program contains an assessment mechanism, indicators, and a management planning component. As such, the program could serve as an informative model for biomass sustainability standard development. Just as with the proposed BCAP rules regarding conservation planning (*17*), CRP regulations (*72*) require producers enrolled in the program to prepare a conservation plan approved by CCC according to CCC guidelines. The regulations do not reference specifically these guidelines as separate from those maintained by NRCS. FSA ranks applications according to its Environmental Benefits Index (EBI) (*74*). Not unlike the CMT for the CSP (*69*), FSA assigns each chosen environmental factor a point score. The factors used by FSA (*74*) include: (1) wildlife habitat enhancement from cover crops; (2) water quality benefits of reduced erosion, runoff, and leaching; (3) on-farm benefits of reduced erosion; (4) benefits "likely to endure beyond the contract period"; (5) air quality benefits from reduced erosion; and (6) cost. FSA (*74*) awards increased value to cover crops that provide the most benefits to wildlife, particularly native mixes and designated wildlife priority zones. While it is unclear what methodology is used to assign values to these environmental benefits, it is important to note that in order to gain certain wildlife habitat points, FSA requires (*74*) producers to prepare a wildlife conservation plan.

Concluding Thoughts

As bioenergy policies continue to evolve, so does the definition of "renewable" or "sustainable" biomass. Inconsistent, non-existent, or ambiguous legislation and rules, coupled with the lack of long-term experience measuring specifically the sustainability parameters of biomass, will pose challenges to U.S. regulators and the regulated community moving forward unless policymakers take measures to coordinate and fortify policies. In the absence of such policies, private standard setting has stepped in to fill the void. Both public and private standards, however, would benefit from considering what existing tools producers could use in meeting any future sustainability requirements.

An effective bioenergy policy must start by placing first and second generation biomass on even footing with regard to sustainability expectations. Specifically, all agricultural policies should reward consistently the environmental benefits that flow from perennial cropping as opposed to traditional commodity cropping practices. While EPA's continued refinement of life cycle analysis under RFS2 (*19*) has benefited corn and soy-based fuels, when USDA finalized its BCAP implementing rule (*17*), it failed to include any provision that would reward, for example, perennials' ability to reduce GHG emissions. On the flip side, while the EPA resisted the use of sustainability certification as a method of complying with the land conservation proscription in its Final Rule for RFS2 (*19*) (corn start is "renewable biomass" under the RFS2), USDA's BCAP rule that only applies to perennial crops and residues (*17*) requires producers to maintain an NRCS conservation plan. Despite the fact that cultivation of perennial energy crops (e.g., grasses such as miscanthus and switchgrass) can likely provide environmental benefits superior to monocropped corn or soy, they are nonetheless subject to conservation planning in order to receive BCAP subsidies while corn and soy are permitted to qualify for RFS2 with no conservation planning in place. If Title I crops (i.e., corn and soy) are permitted to be utilized as feedstocks for "renewable" fuels, then they too should be required to meet the same minimum sustainability requirements.

In contrast to the inconsistencies amongst federal agencies, California appears to be doing a better a job of ensuring that its biomass sustainability policies are consistent between its agencies and programs. Mechanisms such as its A.B. 32 Scoping Plan (*75*) and Bioenergy Action Plan (*76*) provide an "umbrella" that guides consistent development of all GHG-related bioenergy projects in the state. Also, policy processes in California are fairly transparent due to the fact that interagency groups such as the Interagency Forestry and Bioenergy Working Group (*77*) make their meetings open to the public and easily accessible online. By contrast, the inner workings (e.g., meetings and documents) of President Obama's Biofuels Interagency Working Group are not readily available to the public; therefore, it is unclear whether the group will consider recommendations for consistent sustainability definitions in light of the President's recently announced "integrated approach" (*4*). This lack of transparency at the federal level also is evidenced by the accessibility of comments submitted regarding proposed regulations or other internal policies. Despite the fact that EPA was able to successfully post thousands of public comments to its RFS2 proposed rule on the regulations.gov web site, when FSA sought comment on its proposed rule for BCAP, only a small portion of the over 20,000 comments received were posted. The public, therefore, is left to rely on the agency's summary of comments, which might omit many pieces of important information that could be beneficial to further research and inform future policies. In selecting BCAP project areas, FSA employees advise potential applicants informally about sustainability requirements, and thus less saavy potential applicants and the research community remain unaware of informal policies.

If biomass sustainability requirements are to help biofuels in fulfilling their promise as a truly "renewable" energy source, stakeholder must consider exactly what these sustainability requirements should look like. The option that appears most efficient to implement is to require NRCS conservation planning for all bioenergy feedstocks that receive federal subsidies. As discussed in this Chapter, NRCS has an extensive framework already in place for identifying environmental concerns, addressing those concerns through practice standards, and helping producers implement and monitor those practice standards through conservation planning. While this option appears to make sense from a theoretical perspective, in reality it no doubt would require a significant increase in NRCS's already limited budget.

Funding concerns aside, another obstacle to adopting NRSC's conservation framework is that NRCS practice standards and models not yet are fully specified to the unique characteristics of second-generation biomass crops such as miscanthus. For example, GHG emissions and carbon sequestration are not considered specifically within NRCS's framework, except to the extent that soil organic matter might serve as a proxy. Compounding the challenge is that agronomic GHG models still are being developed. NRCS, therefore, will have to continually incorporate ever-evolving scientific understanding on the GHG dynamics of agronomic practices. Once it is developed and accessible, NRCS might be able to seek guidance from the "best practices database" for biomass cropping that was created by the 2008 Farm Bill's Agricultural Bioenergy Feedstock and Energy Efficiency Research and Extension Initiative (*78*). Through this initiative (*78*), grant funding will be made available for research that will close many of the knowledge gaps in biomass production (e.g., nutrient management, crop species selection, best management practices, environmental impacts, and production economics). As this effort will take the form of an ongoing process, NRCS should avail itself of its existing framework for developing interim practice standards so that sustainable practices can be adopted and implemented as timely as possible.

As noted by Butler et al. (*79*), "[a]ssessing the impact of [sustainable farming practices] on biodiversity and ecosystem services is fundamental" to "the reconciliation of demands for biodiversity conservation and increased agricultural production" inherent in sustainable development policy. Despite accountability mechanisms for conservation programs being in place since at least the enactment of the Soil and Water Resource Conservation Act of 1977 (RCA) (*80*), some still question whether the NRCS conservation framework alone can achieve significant sustainability gains regardless of the amount of data that USDA gathers on environmental performance. When additional conservation programs were added in the 2002 Farm Bill (e.g., CSP and EQIP) (*81*), NRCS initiated the Conservation Effects Assessment Project (CEAP). As reported by Duriancik et al. (*82*), the Project brought together multiple federal agencies to scientifically quantify the beneficial effects of USDA's conservation programs and assess the potential to improve upon existing conservation practices.

These same authors (*82*) noted that the three core elements of CEAP include regional and national assessments of how conservation practices can meet environmental goals within different ecological systems (e.g., cropland, wildlife, wetlands, and grazing lands), watershed-focused assessments, and identification of current knowledge through literature reviews and workshops to identify the state of current science and gaps in scientific understanding. In 2005, a blue ribbon panel (*83*) led by the Soil and Water Conservation Society was created by USDA to assess its plan and make recommendations on how to ensure CEAP's credibility and utility. From the discussions that ensued, Duriancik et al. reported (*82*) that four framework questions emerged: (1) what should be measured, and how should watershed or landscape level effects be accounted for; (2) what are the scientific methods that can be used to evaluate these effects; (3) how should practices within the landscape or watershed be targeted to improve outcomes; and (4) what are realistic expectations of the time it will take conservation practices to achieve environmental improvement? These questions should logically be applied to any evaluation of a biomass feedstock sustainability scheme.

The Panel (*83*) issued several recommendations at the conclusion of its assessment. First, it logically suggested (*83*) that USDA must determine what should be ultimately accomplished before measuring the effects of conservation practices. In making this determination, NRCS partly could rely on resource assessments done in conjunction with its conservation planning to determine what areas require priority attention. Furthermore, the Panel urged (*83*) USDA to take into consideration the context in which a given effect occurs (e.g., an effect in a highly sensitive watershed or wildlife habitat is greater than one accomplished in isolation or in less sensitive areas). The Panel also emphasized (*83*) actual monitoring as opposed to modeling due to the notion that modeling can be plagued by "uncertainty and error" as a result of missing data, the inability to accurately correlate a practice with an effect, and the difficulty in simulating complex ecosystem functions. The Panel further urged (*83*) Congress to reauthorize the RCA to provide further support and an umbrella framework for all assessments of federal conservation activities, which Congress did in the 2008 Farm Bill (*84*). Pursuant to the RCA and 2008 Farm Bill amendments (*80*, *84*), NRCS must report its assessment of conservation practices and their effects to Congress in 2011. The timing of this report could be critical to continued funding of biomass-related programs, particularly if biomass' potential is highlighted. Finally, the Panel recommended (*83*) that the Office of Management and Budget, which plays a key role in reviewing final regulations, should focus on evaluating overall, cumulative outcomes of conservation programs using their Program Assessment and Rating Tool. Although not addressed in the Panel's report, policymakers should consider what role assessments done pursuant Executive Orders or the National Environmental Policy Act (*85*) could play in evaluating the likely effects of conservation practices. In light of all of these disparate assessment efforts, Congress and the Executive Branch should consider unifying all of these different assessments into one omnibus agricultural scheme for setting environmental goals and measuring practices' effects.

In addition to the sustainability assessments that are occurring, the CSBP (*9*) through its standards development will provide the type of ground level assessment and monitoring recommended by the CEAP blue ribbon panel. During the 2010-2012 growing seasons, the CSBP is field-testing its provisional standard (*9*) at a scale large enough to at least initially gauge the effect of sustainability practices for energy biomass. Not only will national NRCS representatives be participating in the CSBP process as advisors, but producers will also be working with their local NRCS offices to identify and solidify synergies between the NRCS framework and the CSBP provisional standard. Results of each field-test will be incorporated by the Council into its standard and modifications will be made as necessary and as knowledge evolves.

Policymakers also should consider how the measurement tools and other sustainability ranking mechanisms in various federal conservation subsidy programs could be integrated into federal sustainability policy for biomass. For example, these tools and mechanisms could inform how priorities are set for BCAP payments. Just like with the CSP, CRP, WHIP and EQIP programs, it is arguable that priority for limited BCAP funding should be given to those projects that can prove a certain level of environmental benefits will be achieved. Conceivably, Congress should create one sustainability scoring mechanism with consistent goals and accompanying qualifying practices, and that incorporates concepts such as additionality. This would not only streamline efforts at the NRCS in developing evaluation tools and practice standards, but also eliminate redundancy for producers. Furthermore, as demand for agricultural acreage inevitably grows, incorporating sustainability considerations across-the-board (i.e., inclusion in all agricultural subsidy or incentives programs), however, could worsen the "food versus fuel" debate in the short term, as incrased sustainability likely would raise commodity food prices. To the extent biomass could be encouraged on marginal lands to ameliorate competition with food for land, discussions are only beginning in policy circles as to what, from a sustainability standpoint, makes land "marginal." In sum, despite the availability of some existing tools to measure and implement sustainability provisions for biomass, many sustainability-related questions will continue to confront policymakes in the future.

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