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Convergence of Agriculture and Energy: II. Producing Cellulosic Biomass for Biofuels

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Introduction

Increasing global demand for energy is leading the call for energy conservation and use of renewable fuels.

Global energy demand is increasing as known global petroleum supplies are decreasing. Calls to supplement or replace the current fossil-based energy system with new, environmentally and economically sustainable strategies continue to increase, especially in light of more expensive traditional energy sources. Various governmental agencies and working groups have set aggressive targets and timelines for decreasing fossil fuel consumption by substituting bio-based energy (Bush 2007; Foust et al. 2007; Perlack et al. 2005; Smith et al. 2004). The alignment and continuity of these goals is illustrated in Figure 1.

Current grain cropping systems are designed to optimize grain production, not cellulose-containing biomass.

Current biofuel production in the United States relies primarily on corn grain conversion to ethanol, but future systems are expected to depend more intensively on plant biomass than on grain as a feedstock for production of ethanol and other biofuels. In addition, current cropping systems generally are designed to optimize grain production and are not designed to harvest all the aboveground portion of the plant for cellulose-containing biomass. Significant, immediate national investments are needed, along with changes in policy, to address challenges limiting the sustainable production and efficient use of cellulosic biomass as a fuel feedstock to meet anticipated U.S. demand.

The President's "20 in 10 Plan" outlines a combination of technologies, processes, and practices for bio-based energy production.

The Bush Administration outlined a portfolio of recommended technologies, processes, and practices for bio-based energy production that targets improved rates of feedstock conversion and greater efficiency in energy use. The plan also states that a significant portion of the nation's 2017 energy supply, especially transportation fuel, will come from conversion of biomass feedstock to liquid fuels. Considering just the biomass-derived fuels contribution,

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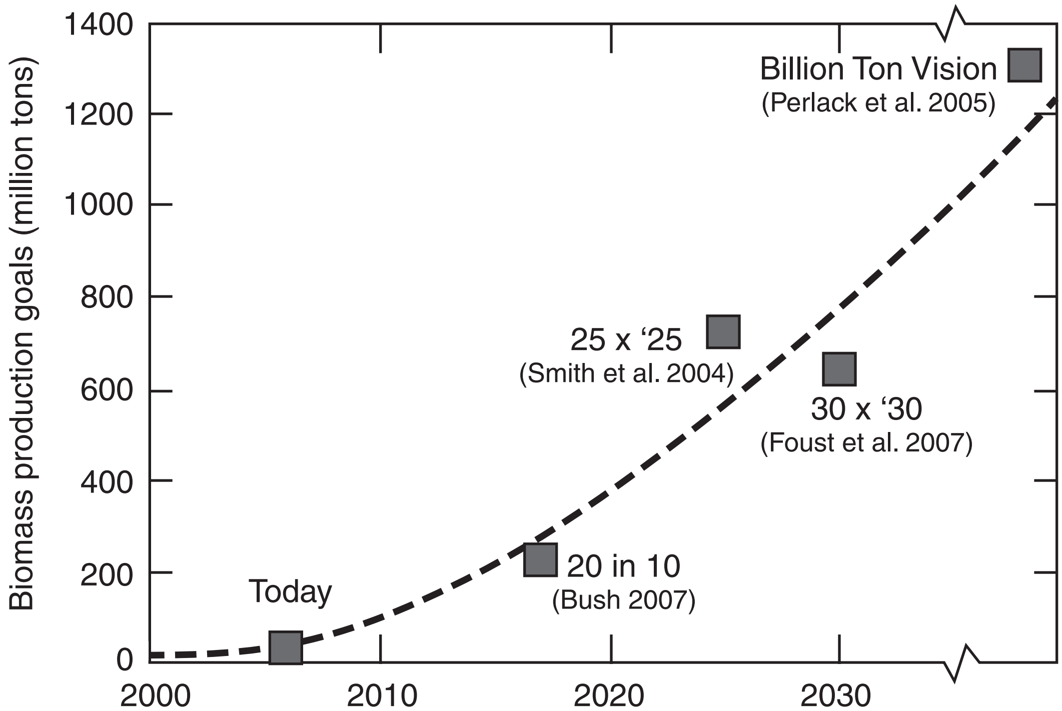

Figure 1. All reports conclude that the quantities of biomass required to achieve fuel-displacement goals are significantly greater than present amounts of biomass harvested for energy production.

roughly 250 million tons or more of grain and cellulosic biomass per year will be needed to reach the 10-year goal, and 650 to 700 million tons per year of biomass to reach the 2025 goal (Figure 1).

Large-scale biofuel production will require more feedstock than offered by corn grain alone; ethanol from cellulosic feedstocks is projected to fill this gap.

Grain ethanol produced from starch is the first step to introducing renewable energy into the fuel system. In a recent commentary paper, CAST (2006) summarized realities for grain ethanol production and listed research and policy needs for long-term success of the industry. A major concern is the impact current and planned grain ethanol production capacity will have on grain prices and availability of corn for traditional uses. Large-scale biofuel production will require much more feedstock than offered by corn grain alone, and ethanol from cellulosic feedstocks is projected to fill this gap (Perlack et al. 2005). The massive amounts of feedstock needed to accomplish these biofuel goals (Figure 1) currently are not being harvested for energy or simply are not available. Bold and optimistic assumptions in some reports indicate future production systems have the capacity to meet the projected feedstock demand (Perlack et al. 2005; Smith et al. 2004). Nevertheless, for the projections to become reality, production, harvest, and processing practices for cellulosic feedstock must be *sustainable* and *profitable* for the biomass producer and the biorefinery operator.

As the cellulosic ethanol industry emerges, all aspects of the production system are new and inherently inefficient and need to be improved simultaneously.

Biomass resource development, supply and conversion systems, crop genetics, and agronomic management practices must be improved to meet the challenge of an agricultural system that produces food, feed, fiber, *and* fuel. Near-term obstacles for the emerging cellulosic ethanol industry are the inefficiencies associated with immature feedstock production practices, marketing and logistics systems, and conversion processes. In other words, all aspects of the industry are new and inherently inefficient. If biofuels technology is not mature in all aspects from supply to end product distribution, it will be only partially able to accommodate the higher feedstock prices that are caused by supply/demand effects.

For both gasoline and grain ethanol, which are mature technologies, feedstocks comprise more than 50% of the cost of production (EIA 2006; Shapouri and Gallagher 2005). Because the biofuels technology is in its infancy, the first commercial cellulosic biorefineries will be able to devote only approximately 40% of the cost of producing a gallon of ethanol to feedstock input (Aden et al. 2002; Foust et al. 2007). This revenue limitation is made even more problematic because the industry depends on not only new conversion technologies but new feedstocks and delivery systems, as well. Currently, the estimated cost of producing and delivering large quantities of dedicated cellulosic biomass for ethanol production exceeds 40% of the estimated ethanol production cost (Kumara and Sokhansanj 2007). Cost reductions in feedstock production, supply-logistics technologies, and cellulosic conversion associated with industry maturation will improve the economic competitiveness of biofuels. Near term, however, policy solutions are needed if cellulosic biomass ethanol production is to be sufficiently profitable to become a major component of the transportation fuel system.

Research, Development, and Policy Needed to Achieve Goals

> Develop a comprehensive, coordinated national plan advancing sustainable bioenergy production.

Achieving a sustainable energy future will require major new investments in research and development (R&D), as well as key policy initiatives to overcome existing technical, ideological, and economic obstacles. Table 1 shows several research, development, policy, and educational actions that are needed to grow, harvest, and deliver—in an economically and environmentally sustainable manner—the quantities of biomass needed to produce ethanol to achieve fuel-offset goals. Existing R&D efforts are spread across federal agencies, state governments, universities, and private industry. Developing a comprehensive, coordinated, widely accepted and publicized set of goals and completing an overall national strategic plan with realistic goals and assigned responsibilities may be the most important short-term actions needed. The coordinating efforts at the federal agency level, as summarized in the National Biofuels Action Plan (2006), are acknowledged, but broader integration and more specific delineation of responsibilities are necessary.

Actions are needed in several focus areas (Table 1) to ensure production and delivery of feedstock in the volumes needed to achieve established goals (Figure 1). Actions can be categorized as "immediate" (measures that are critical within the next 10 years to promote and foster development of biomass feedstock and ethanol production systems), and "continuing" (measures necessary to sustain a cellulosic bioeconomy and to achieve longer-term energy policy objectives).

Focus Area: Resource Assessment

> Refine and regionalize the Billion Ton Vision assessment of current biomass supply and future production capacities.

> Expand the National Agricultural Statistics Service database to include biomass production by crop and county based on geospatial data.

The validity of estimates in the Billion Ton Vision has been discussed in the literature (Lal and Pimentel 2007), but the estimates need to be verified and regionalized. The biofuel industry will need reliable, realistic appraisals of current and future feedstock supplies in addition to evaluation of the supply stability. These assessments must occur at two levels. First, state- or region-specific inventories of current and projected feedstock production capacity are needed. Second, national crop yield databases must be expanded to include biomass yield data for all major and prospective cellulosic feedstock crops. Data should be reported on an agro-ecoregion/soil resource basis. Reliable biomass inventories and projections will aid business planning and policy development greatly.

Focus Area: Agronomic Systems

> Encourage sustainable feedstock production as a co-component of existing food, feed, and fiber production systems to provide biomass for early-generation cellulosic ethanol processors.

Research is needed to identify sustainable biomass feedstock production systems. These production practices must maintain or enhance soil fertility, productivity, and soil organic carbon (SOC) and must control erosion. Although both traditional and renovated versions of current production systems are needed to grow the massive amount of feedstock required, the ideal approach may involve cultivated perennial crops that decrease tillage frequency, increase biomass partitioned below ground, and exhibit beneficial ecosystem services such as improved wildlife habitat and enhanced air and water quality. To be a viable source of biomass, these production methods also must offer high yields and high efficiency of input use.

Table 1. The immediate and continuing actions needed to grow, harvest, and deliver the quantities of biomass necessary to produce ethanol to achieve fuel-offset goals

		Actions	
		Immediate (within 10 years—230 million tons/year)	**Continuing** (over the next 20 years—700 million tons/year)
Research & Development/Policy Focus Areas to Achieve Goals	**Resource Assessment**	• Produce accessible state/regional inventories of current and projected cellulosic feedstocks. • POLICY: Expand national crop yield databases (USDA–NASS) to include cellulosic feedstocks.	• Expand the USDA–NASS database to include geospatial reports and crop model-based predictions for cellulosic biomass commodity production and futures trading.
	Agronomic Systems	• Develop sustainable, site-specific guidelines and practices for crop residue removal that do not violate agronomic constraints or impair the environment. • Develop agronomic systems that lower biomass production costs. • POLICY: Vastly increase research investments to develop systems that maximize sustainable production of biomass feedstock.	• Integrate new energy crops and management strategies into current cropping systems. • Develop cropping systems to enhance annual capture of carbon on croplands and improve input use efficiency. • POLICY: Develop conservation programs and rules that accommodate and encourage sustainable production of cellulosic feedstock.
	Crop Development	• Develop existing and new crops with enhanced cellulosic yield and ethanol conversion efficiencies. • POLICY: Increase investment in development of germplasm for new or unconventional crops with feedstock production potential.	• Deploy new high-yielding energy crops with significantly improved photosynthetic capacity and increased stress tolerance. • POLICY: Implement policies and commodity programs that facilitate introduction and use of new cellulosic crops.
	Feedstock Supply Logistics	• Develop engineered supply system technologies that reduce feedstock supply logistics costs to no more than 25% of total ethanol production costs. • POLICY: Implement financing, permitting, and regulatory programs and policies encouraging development of more efficient feedstock supply systems.	• Develop a common commodity-scale feedstock supply system for all cellulosic biomass resources, geographic regions, and conversion technologies.
	EducatIon and Extension	• Develop educational programs to train the professional work force needed for the bioeconomy.	• Create educational programs to advance public understanding of the new bioeconomy and need for stricter energy conservation policies.

Expand crop production and management research for major agro-ecoregions to maintain soil organic carbon and sustain the soil resource.

Agronomic systems will be location specific, but maximizing the efficient use of inputs (e.g., light, water, carbon dioxide [CO_2], nutrients, and pesticides) will be common to all systems. Key to development of these systems will be the expansion of agronomic trials for each major agro-ecosystem and the creation of scientifically based modeling tools to predict the impact of management changes associated with bioenergy cropping systems. This major research investment is needed to develop (1) the baseline data and information to devise site-specific practices that optimize yields while controlling erosion and maintaining or improving SOC, and (2) the use of harvesting systems capable of collecting biomass at appropriate rates on sites with diverse characteristics.

Focus Area: Crop Development

Develop and deploy advanced energy crops with associated sustainable and profitable production systems.

Although progress can be made by adapting current crop species and varieties to sustainable feedstock production systems, gains needed to produce the amounts of biomass, and in turn ethanol, targeted for the next 10 to 20 years (Figure 1) will require cultivars specifically designed for this purpose. Priority must be given to developing biomass crops with high yield, input use efficiency, and composition customized to the selected processing method. Any new plants identified for biomass production should pose little, if any, risk of becoming invasive (CAST 2007).

Because most plant breeding work during the past 50 years has focused on improved grain yield of commodity crops such as corn and soybean, there has been relatively little effort to improve or develop biomass energy crops—beyond comparatively minor efforts to enhance yield in forage crops (Traxler et al. 2005). Public support for improvement of "forage and minor crops" has essentially disappeared. For example, despite the U.S. government's championing switchgrass as a prominent biomass feedstock, the species has received relatively little support and attention by the plant breeding community because of inadequate funding. Lack of current support is not a reflection of limited potential for yield improvement (Hopkins et al. 1995), but simply a failure of public agencies to put forward a cohesive, coordinated interagency plan for addressing critical aspects of recent energy security plans or goals. In addition to increased yield and quality, improvement is needed in tolerance to stresses such as low soil fertility, low temperature, drought, and salinity.

Expand investment in breeding and genetic improvement of dedicated energy crops.

Plant breeding is a long-term undertaking, frequently requiring 10 years (or longer for perennials) to bring a new variety to market. But increased knowledge of the genetic, physiological, and biochemical principles underlying specific traits, combined with new genetic enhancement tools such as marker-assisted breeding and quantitative trait loci mapping, has the potential to accelerate the breeding process. New biomass crop development is needed and must include a commitment to, and investment in, building scientific capacity in plant genetics, physiology, biochemistry, genomics, breeding, and production systems for these new or evolving crops.

Focus Area: Feedstock Supply Logistics

Develop supply systems to decrease feedstock logistics costs to less than 25% of ethanol production costs.

Feedstock supply-system logistics encompasses those operations necessary to move biomass from the land to the biorefinery. Collectively, these harvesting, transporting, and preprocessing activities represent one of the largest challenges to the success of this industry. Although actual costs depend on a host of factors, feedstock production and logistics currently constitute an estimated 35 to 65% of the total production costs of cellulosic ethanol, whereas logistics associated with moving the biomass from the land to the biorefinery can comprise an estimated 50 to 75% of those costs. If feedstock logistics costs exceed 25% of the total biomass ethanol production costs in the mature industry, very little margin remains in the system for biomass producers and biorefinery operators. Improvements in feedstock supply system equipment capacities, equipment efficiencies, and biomass quality will lead to enhanced conversion and, in turn, create revenue to be shared among the feedstock producer, supplier, and refiner.

Supply-logistics costs vary substantially among regions, depending on weather, cropping systems, transport load limits and other regulations, crop and feedstock type, and storage method. For example, regional differences in load limits can change supply-logistics costs by more than \$2.00 dry ton^{-1}. Improvements in feedstock density and flow characteristics are crucial to optimize collection and handling activities, decrease supply-system energy use, standardize biomass format, and maximize revenue in the biomass ethanol production system. Capital investments and policy/permitting issues for new biomass logistics equipment will rival the investment needed to construct biorefineries. Policy issues include financial programs, air quality, fire codes, road load limits, and many others.

Focus Area: Education and Extension

Create bioenergy and bioeconomy public education programs.

The public needs information to evaluate the benefits and costs associated with moving from a petroleum-based to a bio-based economy. Extension education programs on cropping options and practices for biofuels production and harvest will be essential components of a secure energy future. General educational programs should include all aspects of bioenergy, including "food and feed vs. fuel" issues, environmental considerations, and life-cycle net energy returns. In addition, the public needs to be educated on the carbon footprint of different transportation fuels, as well as the need for energy conservation as an essential component of a successful national energy strategy. It is critical that the public and policymakers understand, and accept, that working only on supply-side issues will not solve energy problems. Decreased demand through conservation and improved efficiency in energy-using systems also are needed.

Establish programs to create a skilled workforce, including scientists and engineers, for the bioeconomy.

A bio-based energy economy will require a workforce with skills and knowledge to operate equipment and processing plants designed to convert biomass to fuel. Scientists and engineers trained in plant biology, physiology, and breeding, as well as genomics, agronomy, soil science, and ecology will be needed to sustainably expand the feedstock supply. Public support for research in these fields must be expanded. As new crops and agronomic systems are developed, extension and outreach programs will be needed to educate farmers.

Summary

Demand for biofuel feedstock will dramatically increase the amount of crop dry matter required to satisfy both new and traditional uses for crop output. Simply adjusting the allocation of crop biomass among competing demands will not generate enough feedstock to achieve renewable energy goals. Policies and national goals must be set to address the root cause of the challenge, which is limited feedstock supply. Shifting focus and resources to a more productive end—increasing overall capacity of crop production systems—will increase the potential for dry matter demands to be met.

Create a research and discovery environment fostering development of innovative crops and cropping systems that maximize capture and use of solar radiation and other environmental and crop management inputs.

A new energy strategy must include maximizing the capture and use of light and CO_2 available on every unit of arable land and then using the dry matter in the most efficient manner. Increasing the efficient capture and use of solar radiation (Long et al. 2006) and all crop production inputs will increase the pool of biomass that can be allocated to competing demands (food, feed, fiber, and fuel). These advances must be accompanied by improved harvest, transport, and storage systems, which will be critical to the efficient use of the biomass produced.

Institute mechanisms to continuously and adequately fund R&D to achieve bioenergy and renewable energy production-and-use goals and mandates.

Well-designed policy and educational efforts will foster rapid adoption of current agronomic knowledge to expand the productivity and efficiency of input use. New knowledge and technology will be needed to ensure that sustainable biomass production capacity will increase with the demand for feedstock as the industry expands. The simple objective must be to maintain a healthy, productive green canopy on the land at all times. To advance agro-ecosystem production beyond that achievable with existing practices, new knowledge, new systems, and new genetic resources must be created, and the environment for continued discovery must be ongoing.

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