ACHIEVING SUSTAINABLE PRODUCTION
of Agricultural Biomass for Biorefinery Feedstock

Bio
BIOTECHNOLOGY INDUSTRY ORGANIZATION

INDUSTRIAL AND ENVIRONMENTAL SECTION HELPING THE BIOBASED INDUSTRY GROW

FOREWORD

BIO represents more than 1,100 biotechnology companies, academic institutions, state biotechnology centers and related organizations across the United States and 31 other nations. BIO members are involved in the research and development of health-care, agricultural, industrial and environmental and marine biotechnology products.

The BIO Industrial and Environmental Section (IES) member companies are leaders in the field of industrial biotechnology, producing novel enzyme biocatalysts, developing processes to make fuels, biobased products and chemicals from renewable feedstocks, and revolutionizing the manufacturing of pharmaceuticals, food additives, flavorings, and personal care products. The BIO IES members believe that industrial biotechnology can only succeed if it is developed and deployed in partnership with agricultural producers, energy and chemical companies, environmental NGOs, academic experts and government policy makers.

The IES member companies believe that by coupling recent advances in industrial biotechnology with agricultural biotechnology, significant supplies of renewable transportation fuels and other biobased products can be produced to lessen our dependence on foreign petroleum.

The production of large volumes of biofuels will require some major shifts in public policy, farming practices, and increases in government funding to spur construction of commercial-scale biorefineries. Current ethanol production from corn is robust, but in the not-too-distant future larger quantities of agricultural crops and crop residues will be needed as feedstock for biorefineries to produce growing volumes of transportation fuels, polymers and chemicals. BIO commissioned this study to help collect relevant information and data on the sustainable collection of agricultural crop residues for use as biorefinery feedstocks in an effort to advance understanding of this important subject area in all the sectors mentioned above.

Additional information on industrial biotechnology, bioenergy and biobased products can be viewed at the BIO Industrial and Environmental Section website www.BIO.org/ind.

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EXECUTIVE SUMMARY

Demand for alternative feedstocks for fuels, chemicals and a range of commercial products has grown dramatically in the early years of the 21st century, driven by the high price of petroleum, government policy to promote alternatives and reduce dependence on foreign oil, and growing efforts to reduce net emissions of carbon dioxide and other greenhouse gases.

Ethanol production has more than tripled since 2000, with annual U.S. production expected to exceed 7 billion gallons by 2007. Sales of biobased plastics are also expanding.

The growing availability of economically competitive biobased alternatives to petroleum can be attributed in large part to advances in the production and processing of corn grain for industrial uses. Steady increases in corn yields made possible by agricultural biotechnology continue to expand the supply of available grain-based feedstock. Rapid advances in the relatively new field of industrial biotechnology are greatly enhancing the efficiency of ethanol production and making possible a range of new biobased polymers, plastics and textiles from agricultural starting materials.

In order to meet the U.S. Department of Energy (DOE) goal of 60 billion gallons of ethanol production and 30 percent displacement of petroleum by 2030, new feedstock sources will be required to supplement high-efficiency production from grain. A robust sustainable supply chain for cellulosic biomass from agricultural residues and dedicated energy crops will be needed within a few years.

Nearly 1 billion dry tons of cellulosic biomass could be supplied by U.S. agricultural lands in the form of crop residues and dedicated energy crops. A growing list of companies has announced intentions to begin construction of cellulosic biorefineries. One challenge for the emerging cellulosic biomass industry is how to produce, harvest and deliver this abundant feedstock to biorefineries in an economically and environmentally sustainable way.

Corn stover and straw from cereals such as wheat and rice are the most likely cellulosic feedstocks for commercial-scale production of ethanol in the near term, potentially supplying more than 200 million dry tons of feedstock annually within three to five years, enough to triple current ethanol production. Dedicated energy crops such as switchgrass will follow as a feedstock supplement once a market for cellulosic biomass develops further.

Corn stover has the largest potential as a near-term biorefinery feedstock, given its high per-acre yields. Current cropping practices require that most or all stover remain on the field to maintain soil health. As biorefinery construction creates markets for crop residues, farmers will be more motivated to adopt practices that lead to economic and sustainable removal. An environmental and economic 'optimum' removal will balance sufficient retention of residues to avoid erosion losses and maintain soil quality while using excess residue as biorefinery feedstocks. The impact of varying levels of stover and straw removal will depend considerably on local conditions and practices.

Under a range of conditions, no-till cropping allows for substantially greater residue collection than current practice, enabling biorefinery siting in areas where suitable supplies are currently unavailable. Further evolution toward greater no-till cropping is needed in order to supply adequate feedstock while complying with erosion guidelines and maintaining soil quality. Lower operating costs and recent successes have spurred an increase in adoption of no-till, with 16 percent of wheat acreage and 20 percent of corn acreage now under no-till practice. However, no-till is not yet widely utilized in regions of the country with the greatest potential to supply biomass.

Ultimately, growing demand for crop residues will likely prove a strong additional driver for the transition to more widespread no-till cropping. Once a market for agricultural residues develops, individual farmers or groups of farmers may elect to adopt no-till cropping to attract biorefineries to their area. Residue collection may also enable no-till cropping in wetter regions, such as the northern Corn Belt, where excess residues currently hamper germination and reduce yields.

While the economics depend on regional and local conditions, for those not currently practicing no-till the benefits of converting may justify the time to learn new methods and the $50,000 to $100,000 investment in new planting equipment. For instance, a 1,000-acre farm could expect to recover the additional costs through revenue from residue sales in as little as two years.

New markets that commoditize the environmental benefits of no-till farming could provide even greater incentive to convert. Carbon credits for no-till transition currently sell for roughly $1 per acre on the voluntary Chicago Climate Exchange. If mandatory greenhouse gas limits are established in the United States, the carbon credit benefits of no-till adoption could exceed $10 per acre.

In addition to economic benefits for farmers, sustainable production and collection of agricultural residues has the potential to deliver substantial benefits for the environment, such as reduced runoff of soil and fertilizers. But the greatest environmental benefits may be to the global climate through reduced emissions of fossil carbon and enhanced sequestration of soil carbon.

With no-till cropping, sustainable collection of 30 percent of current annual corn stover production would yield over 5 billion gallons of ethanol and reduce net U.S. greenhouse gas emissions by 90 million to 150 million metric tons of carbon dioxide equivalent annually if burned as E85 fuel. This would more than offset the net annual growth in emissions from all sectors of the U.S. economy experienced in 2004.

To realize these benefits, additional infrastructure in collection, storage and transportation is needed to supply biorefineries. Rail transport greatly reduces transportation costs relative to trucking, allowing for a much larger collection area. One-pass harvest, in which grain and residues are collected simultaneously, also offers strong opportunities to lower cost.

To facilitate development of the infrastructure necessary for sustainable production and collection of cellulosic agricultural feedstocks, and to achieve the DOE goal of 30 percent displacement of petroleum with renewable biobased feedstocks by 2030, Congress should consider adopting supportive policy measures in the 2007 Farm Bill, including:

- Funding for accelerated development and production of one-pass harvesting equipment;
- Development and distribution of simple-to-use soil carbon models to allow farmers to compute how much crop residue can be collected without degrading soil quality;
- Support to farmers to assist with transition to no-till cropping for biomass production;
- Incentives for the development and expansion of short line and regional rail networks;
- Funding for demonstration projects to streamline collection, transport and storage of cellulosic crop residue feedstocks;
- Development of a system to monetize greenhouse gas credits generated by production of ethanol and other products from agricultural feedstocks; and
- Funding for programs to help farmers identify and grow the most suitable crops for both food production and cellulosic biomass production.

Cellulosic biomass from agricultural residues and dedicated energy crops represents a highly promising new source of feedstock material for the production of ethanol, renewable chemicals and a range of commercial biobased products. Residues from existing crops can be utilized to greatly expand current biofuels production. American farmers are poised to deliver.

Achieving Sustainable Production of Agricultural Biomass for Biorefinery Feedstock

J. Hettenhaus, CEA Inc. For the Biotechnology Industry Organization Industrial and Environmental Section
November 2006

INTRODUCTION

Can American farmers feed the world and produce large supplies of biomass for a growing biorefinery industry? The answer is yes. Demand for alternative feedstocks for fuels, chemicals and a range of commercial products has grown dramatically in the early years of the 21st century, driven by the high price of crude oil, government policy to promote alternatives and reduce dependence on foreign petroleum, and efforts to reduce net emissions of carbon dioxide and other greenhouse gases. This is particularly true for renewable feedstocks from agricultural sources.

For example, in the United States, ethanol production, primarily from corn grain, has more than tripled since 2000. Annual U.S. production of ethanol is expected to exceed 7 billion gallons by 2007, displacing nearly 5 percent of the projected 145 billion gallons of U.S. gasoline demand.[1] Sales of biobased plastics are also expanding.

The growing availability of economically competitive biobased alternatives to petroleum can be attributed in large part to advances in the production and processing of corn grain for industrial uses. Steady increases in corn yields made possible by agricultural biotechnology continue to expand the supply of available feedstock, while rapid advances in the relatively new field of industrial biotechnology–including development of genetically enhanced microorganisms (GEMs) and specialized industrial enzymes–have greatly enhanced the efficiency of ethanol production.

Industrial biotechnology has also yielded a range of new biobased polymers, plastics and textiles. The U.S. Department of Energy (DOE) has identified 12 building block chemicals that can be produced from biomass and converted to an array of high-value products.[2]

The National Corn Growers Association projects that with continued advances in biotechnologies that boost corn yield, as much as 5.95 billion bushels of U.S. grain could be available for ethanol and biobased products by 2015–while continuing to satisfy food, animal feed and export demands. That amount of corn could produce nearly 18 billion gallons of ethanol, enough to meet over 10 percent of projected U.S. gasoline demand.[3]

But if ethanol is to expand into a more widely available alternative to gasoline, new feedstock sources will be required to supplement high-efficiency production from grain. A robust sustainable supply chain for cellulosic biomass–biological material composed primarily of cellulose, such as agricultural and forestry residues, grasses, even municipal solid waste–is needed.

A recent comprehensive analysis by DOE and the U.S. Department of Agriculture (USDA)[4] found that "in the context of the time required to scale up to a large-scale biorefinery industry, an annual biomass supply of more than 1.3 billion dry tons can be accomplished." Nearly 1 billion dry tons of this could be produced by American farmers, enough to meet the DOE goal of 60 billion gallons of ethanol production and 30 percent displacement of petroleum by 2030.[5]

1 Energy Information Administration, October 2006 Short Term Energy Outlook. http://www.eia.doe.gov/emeu/steo/pub/contents.html.

2 U.S. Department of Energy, "Top Value Added Chemicals from Biomass, Volume I – Results of Screening for Potential Candidates from Sugars and Synthesis Gas." (Washington, D.C., DOE, August 2004.) http://www1.eere.energy.gov/biomass/pdfs/35523.pdf.

3 National Corn Growers Association, "How Much Ethanol Can Come from Corn?" (Washington, D.C., NCGA, 2006.) http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf.

4 Robert D. Perlack, Lynn L. Wright, et al., "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply." ORNL/TM-2005/66. (Oak Ridge, Tenn., ORNL, April 2005.) http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

5 Multi Year Program Plan, 2007 – 2012. (Office of Biomass Programs, EERE, DOE, Aug. 31, 2005.) http://www1.eere.energy.gov/biomass/pdfs/mypp.pdf.

Recent advances in enzymes for the conversion of cellulosic biomass to sugars have brought ethanol from cellulose to the brink of commercial reality. A number of potential producers have announced plans to begin construction of cellulose-processing biorefineries in 2007.

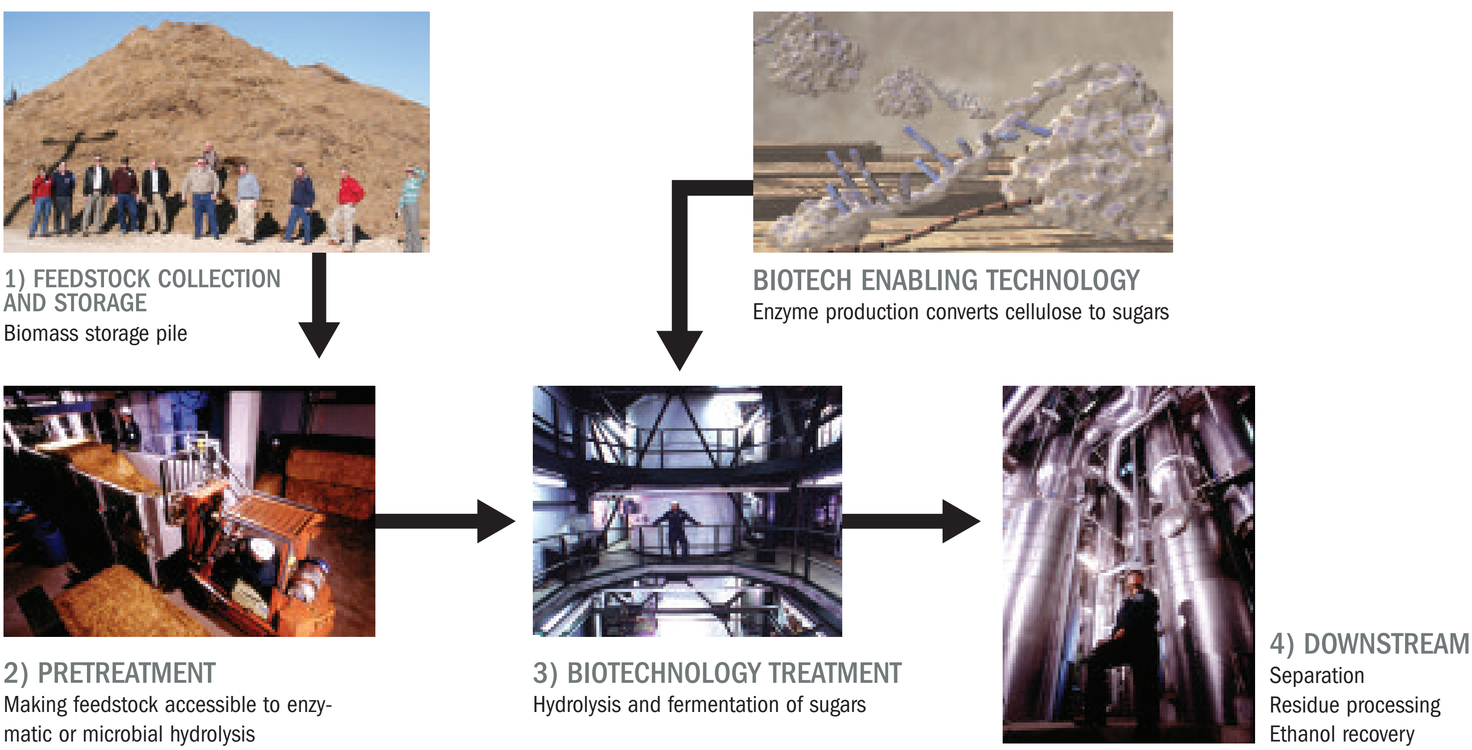
One challenge for the emerging cellulosic biomass industry will be how to produce, harvest, store and deliver large quantities of feedstock to biorefineries in an economically and environmentally sustainable way. Farmers need up-to-date information on the effects of biomass removal to establish a better basis for sustainable collection, since commercial development of biorefineries may occur more quickly than previously believed. An evolution in crop tilling practices toward no-till cropping will likely be needed in order to maintain soil quality while supplying adequate feedstock to these biorefineries. No-till cropping is increasingly practiced but not yet widely utilized in regions of the country with the greatest potential to supply biomass. Additional infrastructure in collection, storage and transportation of biomass is also needed, including equipment for one-pass harvesting and investments in alternatives to trucking, such as short line rail.

But sustainable production and harvest of cellulosic biomass is achievable. Much of the future supply demand can be met by harvesting and utilizing residues from existing crops of corn, wheat, rice and other small grains. Production, collection and processing of these residues will deliver substantial economic and environmental benefits, including significant job creation in rural communities and mitigation of U.S. emissions of greenhouse gases.

This report proposes guidelines for how to achieve sufficient feedstock supplies for new biorefineries through sustainable production, harvest and delivery of agricultural cellulosic biomass, with an emphasis on first steps and solutions to early challenges. The report begins with an analysis of the current biorefinery landscape, followed by an assessment of the availability of cellulosic biomass feedstocks. We examine considerations for sustainable removal, discuss expected economic and environmental benefits, and conclude with policy recommendations to accelerate sustainable harvest.

The report will be of interest to farmers, the renewable fuels and chemicals industry, policy makers and non-governmental organizations (NGOs) in helping to guide the evolution of a biobased economy.

Figure 1: Ethanol Production from Biomass



Sources: J. Hettenhaus, Iogen Corporation, National Renewable Energy Laboratory

THE BIOREFINERY LANDSCAPE

The U.S. ethanol industry is in a period of unprecedented expansion. Record high prices for oil, national security concerns, and federal and state mandates have created a surge in demand for ethanol and other domestic alternative fuels.

The country's first Renewable Fuels Standard (RFS)–a provision of the federal Energy Policy Act of 2005 (EPAct, PL 109-58) requiring fuel blenders to add a growing volume of renewable fuels to the nation's fuel supply beginning in 2006–and the elimination of the gasoline additive methyl tertiary butyl ether (MTBE) in favor of ethanol have created strong upward pressure on current ethanol production capacity.

Construction and expansion of ethanol production facilities has grown rapidly. As of October 2006, 106 ethanol plants were in operation nationwide with an annual production capacity of 5 billion gallons. Nearly all of these facilities are wet or dry mills processing corn grain. Another 55 plants with 3.5 billion gallons additional capacity were under development.[7]

Corn grain supplies are projected to grow to enable production of up to 18 billion gallons of ethanol annually by 2015,[8] but additional feedstock sources will be needed to meet the DOE goal of 60 billion gallons by 2030.

Recognizing the need for new ways to expand production of ethanol, and spurred by recent dramatic advances in industrial biotechnology, several producers have announced plans to begin construction of integrated biorefineries for the production of ethanol from cellulosic biomass. These would be the first commercial ethanol from cellulose biorefineries in the country and some of the first in the world.

WHAT IS A BIOREFINERY?

The National Renewable Energy Laboratory (NREL) defines a biorefinery as "a facility that integrates biomass conversion processes and equipment to produce fuels, power, or chemicals from biomass."[6] Corn mills, which fractionate corn grain into a variety of products, could be considered simple biorefineries. Current ethanol or biopolymer plants add fermentation units and residue processing. But biorefineries that convert cellulosic biomass to ethanol will be substantially more complex, requiring pretreatment and enzyme production units upstream of fermentation and reprocessing of residues for power or co-products. In this scenario the whole corn plant, for instance, will be converted to a variety of products including ethanol, bioplastics, renewable chemicals, food and feed. In the future, biorefineries will likely resemble modern oil refineries and chemical plants. The first oil refineries were merely open kettles. Over time they became more complex and diverse. The same will be true for biorefineries.

Cellulosic Biorefinery Projects in Development

In April 2004, **Iogen Corporation** (www.iogen.ca) delivered the world's first commercial-use ethanol fuel from cellulose (from wheat straw) at their 3 million-liter-per-year (800,000-gallon-per-year) demonstration plant in Ottawa, Canada. Their facility represents the final proving stage prior to the rollout of full-scale commercial ethanol from cellulose biorefineries, each designed to process annually more than 1.5 million dry tons of crop residues into 375 million liters (100 million gallons) of ethanol. The company is working with its partners, including Shell and Petro-Canada, to finalize plant locations.

Abengoa Bioenergy (www.abengoabioenergy.com) is a major ethanol producer and bioenergy technology company in the United States and Europe. The company broke ground in early October 2006 on a one-ton-per-day ethanol from cellulose pilot plant adjacent to its corn dry mill plant in York, Neb. The pilot biorefinery will be integrated to process

6 National Renewable Energy Laboratory, http://www.nrel.gov/biomass/biorefinery.html.

7 Renewable Fuels Association, http://www.ethanolrfa.org/media/press/rfa/view.php?id=903.

8 NCGA, 2006.

Iogen's 3 million-liter-per-year demonstration biorefinery near Ottawa, Canada, is the world's first to process cellulosic biomass into ethanol. Source: Iogen Corporation

cellulose from distiller dry grains (DDGs) and agricultural residues. In addition, Abengoa is currently constructing the world's first commercial-scale ethanol from cellulose demonstration plant, a 5 million-liter-per-year (1.3 million-gallon-per-year) wheat straw to ethanol plant in Salamanca, Spain. The facilities are expected to be operational in 2007 and 2006, respectively.

DuPont (www.dupont.com), a science solutions company with operations in more than 70 countries, has integrated its chemistry and engineering capabilities with biotechnology tools to develop renewably sourced chemicals and fuels. DuPont has teamed with Pioneer, Deere & Company, Michigan State University, NREL and **Diversa** (www.diversa.com), a San Diego-based enzyme provider, to develop an integrated corn-based biorefinery that would produce fuels and chemicals from the entire corn plant. DuPont has also partnered with British petroleum firm **BP** (www.bp.com) to develop biobutanol, a more energy-rich fuel alcohol, first from starch and eventually from cellulose.

Broin (www.Broin.com), a leading ethanol producer, has announced plans to partner with DuPont to add cellulose capacity to an existing corn ethanol facility in Iowa. The plant will use a proprietary technology to remove the cellulose-rich bran from the kernel for processing with corn stover in the cel-

BIOMASS TO ETHANOL: HYDROLYSIS AND FERMENTATION

Sugars are the essential raw material for a range of biobased products from ethanol to bioplastics. In the case of ethanol, sugar is converted into alcohol through fermentation. Both corn grain and cellulosic feedstocks, such as corn stover, straw and wood, are composed of about 70 percent sugars, making them good candidates for ethanol production. The challenge lies in extracting the sugars from these agricultural feedstocks.

In corn grain, the sugars are all of the same variety (6-carbon molecules of glucose), joined together with relatively simple bonds to form starch. These simple bonds can easily be broken using commonly available amylase enzymes and water in a process called hydrolysis.

Isolating the sugars in cellulosic biomass is a considerably more complicated task. Cellulosic biomass is composed of a mixture of 6-carbon glucose sugars in the form of cellulose and 5-carbon pentose sugars linked to other 6-carbon sugars in the form of hemicellulose, all held together by complex chemical bonds bound with a stiff, fibrous substance called lignin. The biomass must first be pre-treated to separate the lignin and loosen the chemical bonds. Cellulase enzymes can then be used to break the sugar-to-sugar bonds via hydrolysis.

Recent biotech advances have made significant improvements in cellulase enzymes and pentose-processing microbes, closing the gap on making cellulosic biomass conversion to ethanol economical. As commercialization proceeds, further gains will help ensure sustainable feedstock platforms for fuels and chemicals.

	Corn crain	Cellulosic biomass
Sugar content	70% as starch.	30-50% as cellulose. 25-32% as hemicellulose.
Conversion to individual sugars	Straightforward conversion to sugars via amylase enzymes. Current starch to sugar conversion cost 3¢ to 5¢ per gallon ethanol.	Challenge to convert to sugars. Cellulose to glucose with much-improved enzymes approaching 10¢ per gallon.
Current ethanol yield	105 to 120 gallons per dry ton (2.5 to 2.8 gallons ethanol per bushel).	80 to 90 gallons per dry ton feedstock. Pentose fermentation to alcohol still an evolving technology.

lulosic unit. Ethanol yield is expected to increase 27 percent per acre. Broin has also partnered with enzyme manufacturer **Novozymes** to develop a cold "no cook" starch hydrolysis process that substantially reduces energy inputs for starch ethanol.

Mascoma (www.mascoma.com) has a cellulose to ethanol technology platform ready for demonstration and commercial projects. With substantial investment from the venture capital community, Mascoma is creating partnerships, engineering designs and financing relationships to jointly develop ethanol from cellulose plants using a variety of feedstocks.

A growing list of less-established companies has also announced intentions to begin construction of cellulosic biorefineries. Many other companies, including Cargill, DSM, Degussa, BASF, and ADM are following these developments closely. Some are expected to move to cellulosic feedstocks once the technology is proven. Others have stated they wish to source fermentation sugars directly, leaving the biomass conversion process to others.

Cellulosic biomass processing is expected to generate in excess of $4 billion annually in feedstock sales in the United States by 2010, growing to more than $15 billion annually by 2020, according to the Biomass Technical Advisory Committee to the USDA and DOE.[9] Anticipating and planning for the arrival of cellulosic biorefineries will better ensure successful implementation, avoiding pitfalls and assuring earlier realization of benefits.

AVAILABILITY OF BIOMASS FEEDSTOCKS

A large, reliable, economic and sustainable feedstock supply is required for a biorefinery. Current yields for ethanol from agricultural residues (corn stover, straw from wheat, rice and other cereals, and sugarcane bagasse) are about 65 gallons per dry ton.[10] Thus, a moderately sized 65 million-gallon-per-year cellulosic biorefinery would need 1 million dry tons per year of feedstock. This could require 500,000 acres or more of cropland–a supply radius of at least 15 miles. The actual supply radius could vary from 15 to 30 or more miles, depending on crop rotation, tillage practices, soil characteristics, topography, weather and farmer participation.

Research at a variety of sites indicates that economic delivery of crop residues is achievable at this radius and beyond–up to 50 miles from the biorefinery site when short line rail transport is available.[11] So, cellulosic biorefineries of well over 100 million gallon capacity are possible.

To sustain a commercial-scale biorefinery, cropland surrounding the site should meet the following criteria:

- **Large Area:** Minimum of 500,000 acres of available cropland;
- **Sustainable:** Cropping practice maintains or enhances long-term health of the soil;
- **Reliable:** Consistent crop supply history with dry harvest weather;
- **Economic:** High-yielding cropland; and
- **Favorable Transport:** Easy access from field to storage and processing facilities.

A recent USDA/DOE study on the technical feasibility of a billion-ton annual supply of biomass for bioenergy and biobased products[12] estimated the potential amount of biomass available on an annual basis from agricultural sources in the United States at

9 Glenn English, Jr., Thomas W. Ewing, et al., "Vision for Bioenergy and Biobased Products in the United States." (Washington, D.C., Biomass Technical Advisory Committee, October 2002.) http://www.biomass.govtools.us/pdfs/BioVision_03_Web.pdf.

10 U.S. Department of Energy, "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda." DOE/SC-0095. (Washington, D.C., U.S. Department of Energy, Office of Science and Office of Energy Efficiency and Renewable Energy, June 2006.) http://doegenomestolife.org/biofuels/b2bworkshop.shtml.

11 James Hettenhaus, BIOMASS FEEDSTOCK SUPPLY: As secure as the pipeline to a Naphtha Cracker? (Presentation at World Congress on Industrial Biotechnology and Bioprocessing, Orlando, Fla., April 21-23, 2004.)

12 Perlack, Wright, et al., 2005.

nearly 1 billion dry tons. Crop residues are the largest anticipated source. Assuming continued strong increases in corn yields from agricultural biotechnology and conversion of present cropping methods to no-till harvest (which allows for greater residue collection), the report estimates that 428 million dry tons of crop residues could be available on an annual basis by 2030. Most of the remainder, 377 million dry tons, is expected to come from new perennial energy crops. The report anticipates the addition of 60 million acres of perennial energy crops as a market develops for cellulosic biomass. The development of high-yielding dedicated energy crops will be a critical element in achieving the DOE goal of 30 percent petroleum displacement.

Of greater interest in the near term (three to five years) is the current sustainable availability of biomass from agricultural lands. Table 1 and Figure 2 show the estimated current availability of agricultural biomass from the USDA/DOE report.

Corn stover is the dominant near-term source of agricultural cellulosic biomass, with substantial contributions from wheat straw, other small grain straw, soybeans and corn fiber. These figures assume a delivered price at the biorefinery of $30 per dry ton.

In colloquies with farmers, potential processors and other stakeholders conducted by DOE during 2001 and again in 2003, there was general agreement that corn stover and cereal straw are the most likely near-term feedstocks for commercial-scale production of ethanol from cellulosic biomass.[13] However, farmers participating in the six Feedstock Roadmap Colloquies stated that the minimum price farmers would accept to collect biomass would be $50 per dry ton, or a return of at least $20 per acre net margin.[14]

At $50 per dry ton, the amount of economically recoverable, sustainably available biomass is more than double the amount estimated in the USDA/DOE report. Over 200 million dry tons of corn stover alone could be collected, enough to triple current ethanol production.

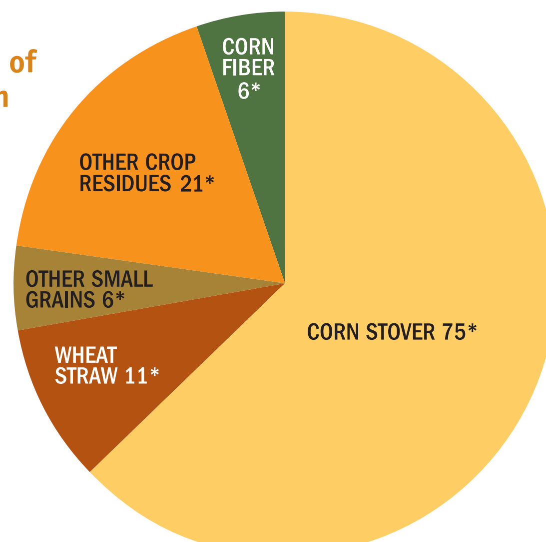
Future availability of feedstocks will depend on several variables, including crop acreage planted to meet competing demands; continued improvements derived from agricultural biotechnology; cropping practices and soil-quality maintenance considerations; and state and federal farm and energy policies. Coordination of farm and energy policies at both state and federal levels can serve to incentivize production, harvest and delivery of a variety of feedstocks to biorefineries.

Table 1: Current Sustainable Availability of Cellulosic Biomass from Agricultural Lands

Source	Currently available biomass (million dry tons per year)
Corn stover	75
Wheat straw	11
Other small grains	6
Other crop residues (oil seeds, soybeans, sugar crops, root crops)	21
Corn fiber	6

Source: Perlack, Wright, et al., 2005.

Figure 2: Pie Chart of Data from Table 1



* Figures above represent millions of dry tons per year.

13 James Hettenhaus, Robert Wooley, John Ashworth, "Sugar Platform Colloquies," Subcontractor Report, NREL/SR-510-31970. (Golden, Colo., National Renewable Energy Laboratory, May 2002.) http://www1.eere.energy.gov/biomass/pdfs/sugar_platform.pdf.

14 James Hettenhaus, Reed Hoskinson and William West, Feedstock Roadmap Colloquies Report: Feedstock Harvesting and Supply Logistics, Research and Development Roadmap. INEEL PO No. 00018408. (Idaho Falls, Idaho, Idaho National Engineering & Environmental Laboratory, Nov. 2003.) http://www.ceassist.com/pdf/feedstock_roadmap_colloquy.pdf#search=%22feedstock%20colloquies%20roadmap'%22.

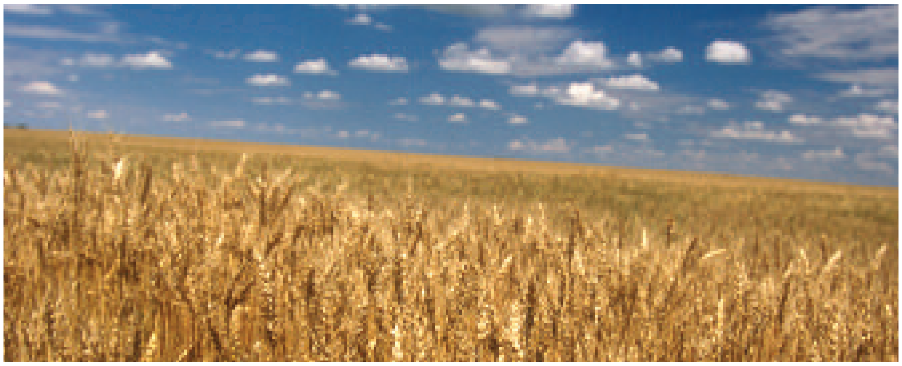
As crop markets change–due to changing demand for food, animal feed, exports, and fuel and consumer products–farmers can be expected to adjust crop planting strategies to maximize their returns. As biorefinery construction creates markets for crop residues, farmers will have to adopt practices that lead to economic and sustainable removal. New models for maintaining soil quality also will be needed. Models based on soil organic material are currently in development.

Feedstock Options

Corn stover and cereal straw make up more than 80 percent of currently available residues under both the USDA/DOE analysis and the $50-per-dry-ton scenario. Corn is the largest grain crop in the United States. Currently, 50 percent of the corn biomass, about 250 million dry tons, is left in the field after harvest. Most of the available cereal straw biomass is from wheat. Rice is also an important source, particularly in Texas and California. Sorghum, barley and oats have smaller potential.

There are significant regional differences in crop characteristics to consider, as well as differences in harvesting mechanics for stover and straw. More corn stover is available than straw, but straw is more readily removed (although in some areas it must be left in the field to retain moisture in the soil). Straw collection infrastructure is generally well developed, while corn stover collection is not. When cereal grain is ready to harvest, straw usually contains 20 percent moisture or less, suitable for baling. In contrast, stover contains 50 percent moisture and must remain in the field to dry and be collected later, depending on the weather. A wet harvest season can prevent its collection entirely.

Corn stover yields are three to five times greater–or more–on a per acre basis than straw from cereal crops. Unless cereal crops are irrigated, there is little straw left to collect. For example, the average dry land wheat straw yield is between 40 and 45 bushels per acre compared to 140 to 200 bushels per acre or more



Top: Stover consists of the stalks, cobs and leaves that are usually left on the ground following corn harvest. Equipment for collection of corn stover must be developed, since few commercial uses for stover currently exist. Source: USDA

Left and above: Baling and collection technology for wheat straw has already been developed for a variety of commercial uses, such as animal bedding, landscape mulch, erosion control, and as a building material. Source: USDA for corn stover. The equivalent of 20 bushels of straw must be left on the surface to comply with erosion guidelines with no-till. The excess is less than one ton of straw per acre. In contrast, leaving 40 bushels of stover with no-till is often sufficient and the excess is four dry tons or more of stover per acre.

Soybean stubble is the surface material left after harvesting of the soy beans. Soybean stubble provides roughly the same feedstock quantity per acre as straw from dryland cereal grains. Little has been published about its removal. More than 60 percent of current soybean acres are no-till, and stubble availability could be considerably larger than straw, especially when a cover crop is included in the rotation to maintain soil quality. Alternatively, stubble availability could be negligible if high corn stover yields drive farmers towards adoption of continuous corn. The availability of soybean stubble will depend on the extent to which soybeans are used in rotation with corn, and the extent to which stubble is available under future tilling practice.

Bagasse presently offers limited opportunities as a feedstock in the United States. Bagasse is the remainder of the sugar cane plant after the sucrose is extracted at the sugar mill. Bagasse is currently burned, often inefficiently, to meet the energy needs of the sugar mill. Efficiency improvements in the burning process could reduce the amount of bagasse needed to power the processing plant by about one third, making excess bagasse available for fuel and chemical production. Production of fuels and chemicals from bagasse would also likely prove more profitable than simply burning it, so an even greater quantity may become available.

However, currently just 6 million dry tons of bagasse is produced in the United States. Even if burned efficiently, only enough for several fuel or chemical plants would be available. Much more cane could be grown if a market for the sugar existed or if the economics for conversion to fermentation sugars were demonstrated.

Straw from rice, such as this variety developed by USDA, is an attractive source of cellulosic biomass. Source: USDA

For rice, as with wheat, large quantities of cellulosic biomass remain on the field after harvest. Source: USDA

MORE BANG FROM BAGASSE

A high-fiber cultivar is under development in California. Switching to a high-fiber cane that is not suitable for sugar extraction but better for biomass conversion may open up considerable opportunity for growers. The high-fiber cane triples the cellulosic biomass available, to 110 tons per acre. Since the higher fiber content decreases the sucrose yield, it only becomes attractive when the bagasse can be processed to higher-value products. Bagasse has a composition close to corn stover. It is thought to have similar pretreatment and hydrolysis processing characteristics.

Corn fiber is being processed on a pilot basis now by several companies, including Aventine Renewable Energy, Inc. (formerly Williams BioEnergy), Broin, Abengoa and ADM. Their efforts are partially funded by DOE.

Corn fiber is a component of DDGs, the co-product of corn dry mill ethanol operations. It is a significant source of cellulose (See Table 2). Because corn fiber is already collected and delivered to ethanol facilities today, it represents a unique opportunity for cellulosic biorefining, since no additional collection or transportation infrastructure is needed. It could also provide an opportunity for farmer co-ops and other participants in grain ethanol production to participate in ethanol production from cellulose.

The biotechnology for corn fiber processing could eventually be applied to corn stover as well, though significant differences exist in the composition, consistency and price of the material. As shown in Table 2, corn fiber contains a small amount of lignin and a large amount of bound starch, while stover contains a much larger lignin fraction.

Process waste from other sources, such as cotton gin trash and paper mill sludge, constitutes an additional potential source of cellulosic residues, especially for niche situations. However, volumes are small and, as with corn fiber, there is no consensus on whether these materials could provide an adequate supply of biomass to warrant biorefinery construction.

Table 2: Corn Fiber and Stover Composition, Dry Basis

	Corn fiber	Stover
Cellulose	12 to 18%	32 to 38%
Hemicellulose	40 to 53%	28 to 32%
Lignin (Phenolic)	0.1 to 1%	15 to 17%
Starch	11 to 22%	None

Dedicated energy crops include herbaceous perennials such as switchgrass, other native prairie grasses and non-native grasses such as Miscanthus, and short-rotation woody crops such as hybrid poplar and willow. There are currently no dedicated energy crops in commercial production, but the high biomass yield of such crops holds tremendous promise. Annual yields in excess of 8 dry tons per acre have already been achieved for both herbaceous and woody crops across a wide variety of conditions, with double this yield in some locations.[15]

The DOE and USDA anticipate that as many as 60 million acres of cropland, cropland pasture, and conservation acreage will be converted to perennial crop production once the technology for converting cellulosic biomass to ethanol is demonstrated at a commercial scale.

Switchgrass is a native perennial once found throughout the U.S. Midwest and Great Plains. Research is under way to develop switchgrass as a dedicated energy crop. Source: Indiana University – Purdue University Fort Wayne, USDA.

15 Perlack, Wright, et al., 2005.

SUSTAINABLE REMOVAL

Cellulosic biomass has the potential to revolutionize traditionally fossil-based industries, radically improving their environmental profile while revitalizing rural economies and enabling energy independence. This vision is only achievable if feedstocks are sustainably produced, harvested and processed.

Farm income expansion is possible only if crops can be grown and harvested without large amounts of fertilizer and other costly inputs. Soil quality enhancement, runoff reduction, greenhouse gas amelioration and other environmental benefits can be achieved with careful attention to production practices. Energy security gains depend on efficient collection, transport and processing of feedstocks. Each of these considerations will vary from region to region, even from farm to farm. Sustainable production practices must be tailored to each operation.

The availability of excess stover and straw for harvesting after erosion requirements are met is dependent on cropping practice and relative economic and environmental benefits. Tillage practice greatly affects availability. No-till practice allows most of the residue to be removed, especially when cover crops are employed.[16] In contrast, conventional tillage leaves less than 30 percent of the surface covered, and there is no excess residue available to remove. Since less than 20 percent of farmers no-till and more than 60 percent conventional till, a major shift in practice is needed for sustainable removal.

Sustainable Production and Harvest

Sustainable delivery of cellulosic biomass feedstocks requires production and collection practices that do not substantially deplete the soil, such that large quantities of biomass may be harvested over sustained periods without sacrificing future yields.

Crop residues serve to both secure soil from erosion and restore nutrients to the soil through decomposition. With biomass removal, there is the potential for degradation of soil quality and increased erosion. From the perspective of soil and environmental quality, determining the amount of excess crop residue available for removal is a complex issue that will vary for different soils and management systems.

An environmental and economic 'optimum' removal balances sufficient retention of residues to avoid erosion losses and maintain soil quality while using excess residue as biomass feedstock. The impact of varying levels of stover and straw removal will depend on local conditions and practices. Farmer involvement in the development of residue collection plans will be critical.

Erosion Control

Past studies of removal effects are helpful, especially for erosion control, but are often incomplete when addressing field removal of crop residues.[17] This is due partly to the wide variation in local conditions and system complexity–it is not an easy task–and partly to skepticism of the need for these studies. Several early attempts at removing biomass for industrial uses failed, and many potential participants remain concerned about soil tilth.

Excess availability of crop residue is dependent on the amount that must remain as soil cover to limit wind and water erosion. Erosion is a function of climate, soil properties, topography, and cropping and support practices such as contour planting and minimum tillage. Water erosion is of greatest concern in the eastern Corn Belt. Wind erosion becomes serious further west.

To determine the amount of surface cover required to meet erosion control guidelines, two models developed by the USDA are widely applied.

For water erosion, the revised universal soil loss equation (RUSLE) developed by the USDA provides guidelines for meeting surface cover requirements.

16 Sustainable Agriculture Network, Managing Cover Crops Profitably, 2nd Ed. (Beltsville, Md., Sustainable Agriculture Network, National Agricultural Library, 2001.) http://www.sare.org/publications/covercrops/covercrops.pdf.

17 See for example L. Mann, V. Tolbert, and J. Cushman, "Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion." Agriculture, Ecosystems and Environment 89: 149-166. 2002.

USDA WIND AND WATER EROSION MODELS

WIND EROSION

E = f (I, K, C, L, V), where E is the wind erosion soil loss.

I is the soil erosion index and relates to the properties of the soil and to the degree of slope of the site. Sandy soil has a higher index than soils with high organic material that easily aggregates.

K is the soil-ridge-roughness factor that considers the soil surface, vegetative cover and ridges on the soil surface.

C is the climatic factor based on wind velocity, soil temperature and water content of the soil.

L refers to the length of the field in the downwind direction. The prevailing wind is normally used.

V is the vegetative cover that relates to amount and condition of the surface cover—whether it is standing or flat, living or dead.

WATER EROSION

T = R * K * LS * C * P, where T is the tolerable soil loss.

R is the rainfall factor, a regional value that does not change here.

K is the soil erodibility factor. K can change significantly from field to field, and even in the same field.

L and S are the slope length and gradient factors. As with K, they vary widely.

C is the crop cover management factor. Type of crop and tillage practice affects C.

P is the factor for support practices such as terracing fields and contour planting.

For local field analysis, the rainfall factor (R) is a constant based on the local climate. The soil erodibility factor (K) and slope (LS) values are set by the field terrain. Support practice (P) is a local factor. It is usually set in consultation with a soil erosion specialist, often the local extension agent.

The crop management factor (C) can be changed by crop selection and tillage practice. For example, soybeans produce 1.5 times the amount of surface material relative to the bean. A field with 40 bushels per acre beans produces 3,600 pounds cover compared to 135 bushels per acre corn and 7,600 pounds cover. If no-till is practiced, much more surface material is available than if the field is tilled, burying some or all of the stubble or stover.

Additional information is available through USDA[18] and Michigan State University.[19]

Wind erosion is a function of the soil's inherent susceptibility to being dislodged by the wind, the soil surface, the local climate, field length and vegetation. Additional information is available at the USDA Wind Erosion Unit website[20] and through the Water Erosion Prediction Project.[21]

Wind erosion of soil must be controlled for sustainable collection of biomass, particularly in the western United States. Source: USDA

Tilling Practice

A transition to conservation tillage practices, in which crops are grown with minimal cultivation of the soil, has been a key element of efforts to encourage more sustainable production of annual crops such as corn and wheat.

Under conventional tillage practices, where soils are intensively tilled to control weeds, deliver soil amendments and aid irrigation, less than 30 percent of the soil is left undisturbed. All residues must be left on the field to prevent soil erosion, leaving no material available for collection.

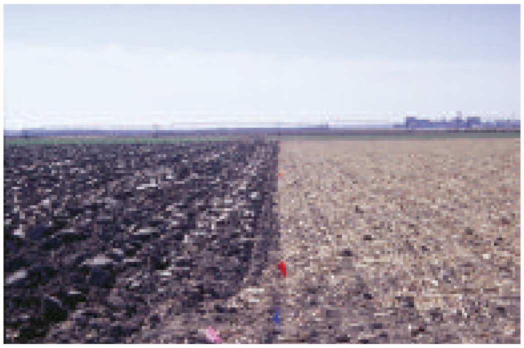
With conservation tillage, 30 percent or more of the soil is left covered. Some residue removal may be possible without threatening erosion control. No-till cropping, in which 100 percent of the soil is left covered, allows for significant harvest of crop residues. Approximately twice

18 http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm.

19 http://www.iwr.msu.edu/rusle/.

20 http://www.weru.ksu.edu/.

21 http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html.



Conventional continuous-till cropping (left) exposes soil to wind and water erosion. No-till cropping leaves soil covered, allowing for removal of substantial amounts of cellulosic biomass without damaging soil. Source: Colorado State University

Roots and stubble are left undisturbed with no-till cropping, securing soil and allowing removal of substantial amounts of cellulosic biomass. Source: Colorado State University

as much residue can be collected under no-till than under partial-till conservation practices.

The impact of tillage practice on feedstock availability for three different plant siting studies is shown in Table 3. Feedstock availability under current tilling practice and anticipated feedstock availability under no-till cropping are determined for each site using USDA Natural Resources Conservation Service (NRCS) erosion models.

Table 3: Feedstock Production & Availability
50-mile radius, dry tons (millions)

Site Study	Produced	Available	
		Current tilling practice	w/No-till
1. Wheat and sorghum, dry land	5.4	0	2.1
2. Corn Belt, dry land	5.4	1.8	3.6
3. Corn Belt, 50% irrigated	5.4	0.6	3.6

All three sites produce the same amount of crop residue according to USDA crop reports. With no-till, all sites could comfortably supply a 1 million-dry-ton biorefinery while complying with erosion guidelines. At the dry land wheat and sorghum site, which featured highly erodible soil, 40 percent of the total residue, 2.1 million dry tons, was available for harvest under no-till cropping. Under current practice for this site, which is nearly all conventional till, no crop residue can be removed.

More stable soils provided 3.6 million dry tons of harvestable residues with no-till at both Corn Belt sites. Current practice reduced the available biomass by 50 percent at the dry land site and by 83 percent at the irrigated site. Corn-bean rotation at the dry land site allowed for greater collection under current practice than the irrigated site, which had more continuous corn with conventional tillage on irrigated acres.

Thus, under a range of conditions, no-till cropping allows for substantially greater residue collection than current practice, enabling biorefinery siting in areas where suitable supplies are currently unavailable.

SOIL MODEL LIMITATIONS

It should be noted that soil erosion models have their limitations. They only indicate if soil is moved, not whether it is removed from a field. The models also do not provide a measure of soil quality. When residue is removed, reduced inputs from the residue to the soil can result in a negative flux from the soil and a loss of soil organic matter and other nutrients, leading to a breakdown of soil structure. Other models are under development to better measure soil quality, but are not expected to replace actual field measurements for some time. Managing for soil carbon quality helps ensure sustainable removal. The Soil Quality Index is recommended: http://csltest.ait.iastate.edu/SoilQualityWebsite/home.htm.

Transitioning to No-till

Currently, more than half of land planted with corn, wheat and other cereals is under conventional tillage, and thus unavailable for residue collection. No-till cropping is practiced on less than 20 percent of current acreage. To realize the full potential of cellulosic agricultural biomass, a significant evolution in cropping practices will be required.

Figure 3 shows adoption rates of no-till cropping for wheat, rice and corn from the most recent analysis by the Conservation Technology Information Center (CTIC http://www.conservationinformation.org/).[22] No-till cropping comprises less than 20 percent of acreage in most counties throughout the country for each of these crops. But large regions with higher adoption rates exist, especially for spring wheat and corn.

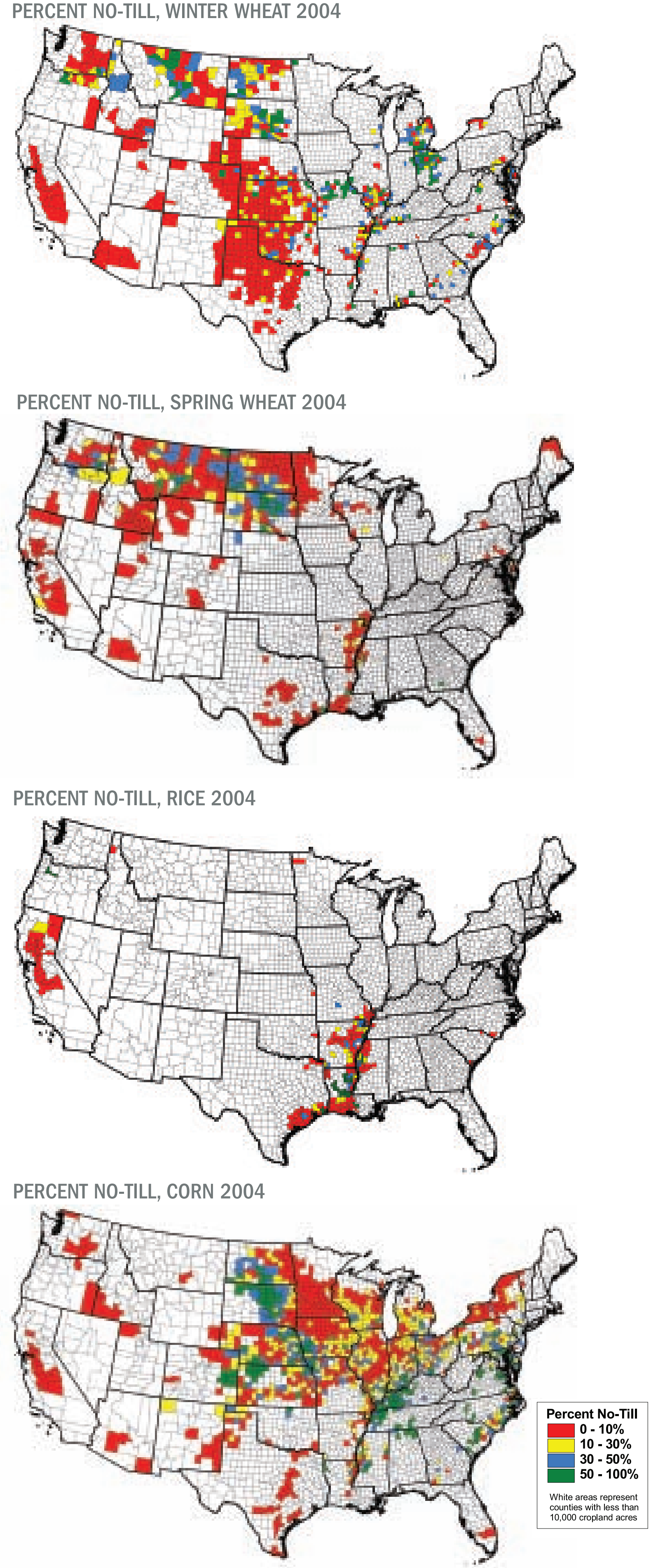
The balance between conservation tillage and conventional tillage has remained relatively unchanged over the past decade, with roughly two thirds of wheat acreage and 60 percent of corn acreage under conventional tillage. Conventional tillage has been used on over 80 percent of rice acreage since data collection began in 2000.

Tables 4, 5 and 6 and Figure 4 show the crop tilling history for wheat, rice and corn based on CTIC surveys.

No-till remains a niche practice for rice, but there is a clear gradual evolution towards greater adoption of no-till for wheat and corn. No-till cropping has proven viable under a range of conditions for both crops. The success of no-till early adopters has prompted neighboring farmers to move to no-till, helping to form the localized regions of enhanced adoption seen in Figure 3.

No-till cropping also tends to reduce fuel and fertilizer use, substantially reducing operating cost. NRCS estimates that no-till cropping saves farmers an average of 3.5 gallons per acre in diesel fuel–an annual savings to farmers of about $500 million.[23] Recent

Figure 3: No-Till Cropping Maps



At right: Adoption rates of no-till cropping for winter wheat, spring wheat, rice and corn. Less than 20 percent of wheat, rice and corn acreage nationwide is under no-till. Source: Conservation Technology Information Center

22 Conservation Technology Information Center, "National Crop Residue Management Survey: Conservation Tillage Data." (W. Lafayette, Ind., CTIC, 2006.) http://www.conservationinformation.org.

23 USDA, Energy and Agriculture – 2007 Farm Bill Theme Paper. (Washington, D.C., August 2006.) http://www.usda.gov/documents/Farmbill07energy.pdf.

price increases for fuel and fertilizer are expected to drive an even greater transition to no-till.

The local climate is a significant factor in considering crop residue removal, and the viability of no-till cropping will depend significantly on local conditions. In more arid regions surface cover is required for moisture retention in the soil. Thus, even with no-till cropping, the amount of residue available for collection in arid regions may be limited. But in wet regions, especially in the northern parts of the Corn Belt, collection of excess stover is desirable, since cooler soils under residues can delay or hamper crop germination and reduce yield. For example, farmers in the eastern Corn Belt have encountered problems with cool, moist soil conditions fostered by no-till's heavy residue cover.

Ultimately, demand for residues will likely prove a strong additional driver for the transition to no-till cropping. Once a market for agricultural residues develops, individual farmers or groups of farmers may elect to adopt no-till cropping to attract biorefineries to the area. Or, as Iogen has done with farmers in Idaho,[24] potential biorefinery project developers may seek out productive farmland and sign supply contracts that could require farmers to adopt no-till practices.

For dedicated energy crops such as switchgrass, tilling is not required on an annual basis, so soil quality maintenance is less of a concern. Most dedicated energy crops are perennial, requiring minimal tillage. Water and wildlife management are likely to be the primary environmental issues. These issues are addressed in considerable detail in a recent report from the Worldwatch Institute.[25]

Table 4: Wheat Cropping Practice
% total acres

WHEAT	No-till	Other conservation-till	Conventional till
1994*	6	25	69
1996*	7	24	69
1998*	9	23	68
2000	10	20	70
2002	12	18	70
2004	16	18	66

* Percentages for 1994–1998 are for all small grain crops. CTIC surveys did not differentiate wheat from other small grains prior to 2000, but wheat comprises over 75 percent of small grain acreage, and cropping trends since 2000 are similar across most small grain crops.

Table 5: Rice Cropping Practice
% total acres

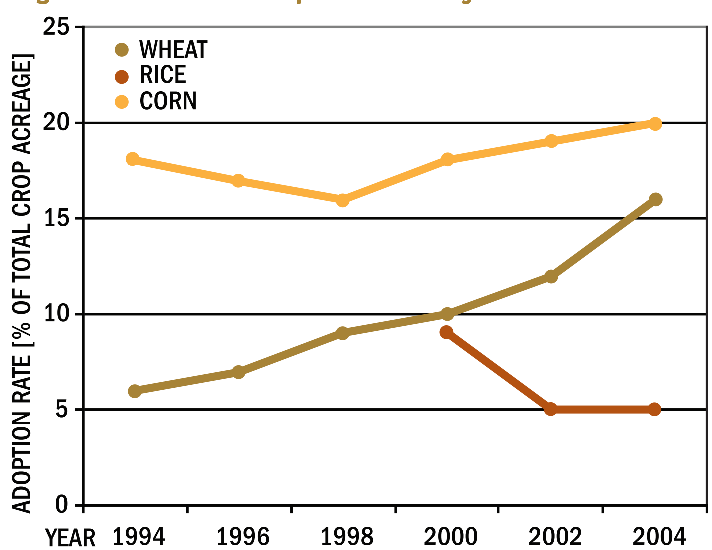
RICE	No-till	Other conservation-till	Conventional till
1994**	–	–	–
1996**	–	–	–
1998**	–	–	–
2000	9	3	82
2002	5	1	94
2004	5	1	94

** Percentages for 1994–1998 are not available. CTIC surveys did not differentiate rice from other small grains prior to 2000.

Table 6: Corn Cropping Practice
% total acres

CORN	No-till	Other conservation-till	Conventional till
1994	18	22	60
1996	17	23	60
1998	16	23	61
2000	18	19	63
2002	19	17	64
2004	20	18	62

Figure 4: No-till Adoption History



Source: Conservation Technology Information Center, http://www.conservationinformation.org

24 Lorraine Cavener, "Stalking Future Feedstocks," Ethanol Producer Magazine. (Grand Forks, N.D., March 2004.) http://www.ethanolproducer.com/article.jsp?article_id=1155&q=stalking%20future%20feedstocks&category_id=29.

25 Worldwatch Institute, "Biofuels for Transportation: Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century." (Washington, D.C., 2006.) http://www.worldwatch.org/taxonomy/term/445.

REALIZING REMOVAL

In addition to production challenges, additional infrastructure in collection, storage and transportation is needed to supply a biorefinery. Farmers in many areas–including Idaho; Harlan, Iowa; Kearney, Neb.; Central Illinois and Southern Wisconsin–have accumulated considerable information on the impact of removing straw and corn stover on their farms and delivering it to a processor. But for the most part this knowledge remains with the farmers, as no outside agencies were involved. Collection of feedstock on the proposed scale for biorefineries–as much as 30 times larger than those studied–will require a large, capable organization with considerable logistical expertise.

SUSTAINABLE COLLECTION CASE STUDY: IMPERIAL YOUNG FARMERS AND RANCHERS PROJECT

With no current market for cellulosic biomass, identifying and overcoming potential obstacles to sustainable collection and delivery is a considerable challenge. But the Young Farmers and Ranchers of Imperial, Neb., have embarked on a study to do just that. With $3 million in funding from USDA and other sources, the Young Farmers are actively experimenting with innovative collection, pre-processing, storage and transport technologies for corn stover to identify logistical challenges and to determine the value of sustainable removal of excess feedstock to farmers and potential processors across the supply chain.

A preliminary study estimated counties within a 50-mile radius of Imperial, Neb. can comply with USDA erosion control guidelines for surface cover requirements and also supply 3.6 million dry tons per year of stover with the adoption of no-till farming practices. Rail service expanded the area supply to 6 million dry tons per year with a $17-per-dry-ton margin to the farmer.

Below: Participants in the Imperial Young Farmers and Ranchers sustainable collection of biomass project stand in front of a 650-dry-ton pile of corn stover. Source: J. Hettenhaus.

A ROLE FOR REGIONAL SUPPLY ORGANIZATIONS

A regional supply organization, in which producers pool their harvests to provide a cohesive feedstock supply, is one way to address the high input demands of future biorefineries. For example, to supply 1.5 million dry tons requires over 500,000 acres, assuming 3 dry tons per acre excess is collected. The number of growers to reach out to for collection quickly becomes a significant and costly challenge. The first 50,000-dry-ton effort to collect corn stover near Harlan, Iowa required 400 farms and more than 30 custom harvesters to collect 30,000 acres.[26] For farmers, a regional supply organization can maximize utilization of collection equipment and help attract new biorefineries by ensuring a reliable supply of feedstock.

Removal Economics

The delivered cost of cellulosic feedstocks has been estimated between $18 and $50 per dry ton. The former is based on one-pass harvesting of crop residue, collected within a 15-mile radius and shipped from collection sites to a processing plant via short line rail 200 miles or less in length. The higher value is for bales delivered within a 50-mile radius. Neither includes a margin for the farmer.

Using $50 per dry ton delivered cost, the relative economics are summarized and compared for baling (Table 7) and one-pass harvest, bulk storage and rail transport from remote collection sites to the processing plant (Table 8).[27]

Table 7: Excess Stover or Straw Sale: Custom Bale and Haul Net to farmer, $/acre(ac)

*Basis: $50/dry ton (dt) delivered, one 30 mi radius collection site, 1.5 Million ac

1 dt/ac left in field	130 bu/ac	170 bu/ac	200 bu/ac
1:1 ratio, 15% moisture, sell	2 dt/ac	3 dt/ac	3.8 dt/ac
Sale, $50/dt	$100	$150	$190
**P & K nutrient credit ($6.20/dt)	(12)	(19)	(24)
***Reduced field operations	10	10	10
Total revenue increase	$98	$141	$176
Less custom bale, $40/ac	(40)	(40)	(40)
Handle, store, $5/dt	(10)	(15)	(19)
Shrinkage, 10%	(10)	(15)	(19)
Hauling, 30 mile radius, $10/dt	(20)	(30)	(38)
Net to farmer, $/ac	$18	$41	$60

*The National Renewable Energy Laboratory uses $30 per dry ton delivered cost to the biorefinery as its base case scenario.[28]

Table 8: Excess Stover or Straw Sale: One-pass Harvest and Rail Net to farmer, $/acre(ac)

Basis: $50/dry ton (dt) delivered, 3-15 mi radius collection sites, 1.5 Million ac

1 dt/ac left in field	130 bu/ac	170 bu/ac	200 bu/ac
1:1 ratio, 15% moisture, sell	2 dt/ac	3 dt/ac	3.8 dt/ac
Sale, $50/dt	$100	$150	$190
P & K nutrients ($6.20/dt)	(12)	(19)	(24)
Reduced field operations, $10/ac	10	10	10
Total revenue increase	$98	$141	$176
Less one-pass harvest, $18/ac	(18)	(18)	(18)
Field to collection site transport, $6/dt	(12)	(18)	(23)
Handle and store stover, $6/dt	(12)	(18)	(23)
Shrinkage, 3%	(3)	(5)	(6)
Rail from collection site, $7/dt	(14)	(21)	(27)
Net to farmer	$38	$61	$79

**The phosphorous and potassium content in straw and stover is typically 0.1 percent and 1 percent respectively, valued at $6.20 per dry ton.[29] The nitrogen fertilizer value is more complex, and depends on crop rotation and local conditions.

***Reduced field operations are estimated to reduce inputs $10 per acre for preparation of the seed bed.

26 D. Glasser, J. Hettenhaus, T. Schechinger, "Corn Stover Collection," BioEnergy '98—Expanding Bioenergy Partnerships: Proceedings, Volume 2, Madison, Wisc., pp 1100-1110, 1998.

27 J.E. Atchison and J.R. Hettenhaus, Innovative Methods for Corn Stover Collecting, Handling, Storing and Transporting. NREL/SR-510-33893. (Golden Colo., National Renewable Energy Lab, March 2003.) http://www.nrel.gov/docs/fy04osti/33893.pdf.

28 A. Aden, M. Ruth, et al., Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL/TP-510-32438. (Golden, Colo., National Renewable Energy Lab, June 2002.) http://www.nrel.gov/docs/fy02osti/32438.pdf.

29 Glassner, Hettenhaus, Schechinger, 1998.

Selling excess stover or straw priced at $50 per dry ton delivered may net the farmer $18 to $60 per acre if baled, depending on the yield, tillage practice, nutrient value, local situation and method of harvest. With one-pass harvest and rail transport, farmer income increases to $38 to $79 per acre.

Rail transport greatly reduces transportation costs relative to trucking, allowing for a much larger collection area. One-pass harvest, in which grain and residues are collected simultaneously, also offers strong opportunities to lower cost and reduce harvest risk. Prototypes are currently under development, funded partially by USDA and DOE projects.[30]

While the economics depend on regional and local conditions, the results serve as a template for evaluating the potential benefits. For those not currently no-tilling, the benefits of converting may justify the time to learn new methods and the $50,000 to $100,000 investment in new planting equipment. At $41 per acre (net farmer income expected with moderate yield and custom bale and haul–Table 7), a 1,000-acre farm could expect to recover the additional investment in as little as two years.

New markets that commoditize the environmental benefits of no-till farming could provide even greater incentive to convert to no-till cropping with one-pass harvest. These markets are developing quickly in anticipation of greenhouse gas regulation in the United States.

30 Graeme Quick, Single-Pass Corn and Stover Harvesters: Development and Performance. Proceedings of the International Conference on Crop Harvesting and Processing, 9-11 February 2003 (Louisville, Ky., USA) 701P1103e.

31 John Sheehan, Andy Aden, Keith Paustian, Kendrick Killian, John Brenner, Marie Walsh and Richard Nelson, Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol, J. Ind. Ecology, Vol. 7, 3-4, 2003.

CLIMATE CHANGE MITIGATION

In addition to economic benefits for farmers, sustainable production and collection of agricultural residues has the potential to deliver substantial benefits for the environment, including reduced runoff of soil and fertilizers. But perhaps the greatest environmental benefits may be to the global climate through reduced emissions of fossil carbon and enhanced sequestration of soil carbon.

The removal of crop residues by its nature reduces the amount of carbon returning to the soil, reducing the rate at which carbon is removed from the atmosphere and stored in the ground. However, studies suggest that this marginal reduction in sequestration is considerably outweighed by the reduction in fossil carbon emissions gained by the substitution of biomass for fossil-based feedstocks and by increased carbon sequestration and reduced field operations resulting from the necessary transition to no-till harvest.[31]

The potential of corn stover for greenhouse gas (GHG) mitigation is summarized in Table 9. Figures are for 80 million dry tons processed per year, which represents 30 percent of the current annual stover production in the United States. Thirty percent is a con-

Table 9: GHG Mitigation from Corn Stover Feedstock
30% US Stover (80 million dry tons) to Ethanol [MMTCO$_2$ eq]

Source	Range
Fossil fuel offset	50–70
Soil carbon increase[32, 33]	30–50
N fertilizer reduction	0–10
Reduced field operations[34]	10–20
Total	90–150

32 Rattan Lal, John M. Kimble, Ronald F. Follett and C. Vernon Cole, The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect (Boca Raton, CRC Press, 1998).

33 C.A. Cambardella and W. J. Gale, "Carbon Dynamics of Surface Residue– and Root-derived Organic Matter under Simulated No-till." Soil Sci. Soc. of Amer. J., 64:190-195 (2000). D.C. Reicosky, et al., "Soil Organic Matter Changes Resulting from Tillage and Biomass Production." Journal of Soil and Water Conservation, 50(3):253 (May 1995).

34 J.S. Kern and M.G. Johnson, "Conservation Tillage Impacts on Soil and Atmospheric Carbon Levels." Soil Sci. Soc. Am. J. 57:200-210 (1993).

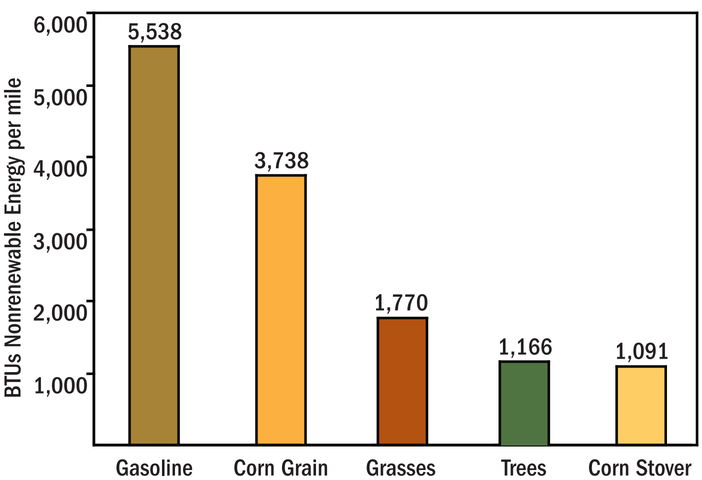
servative estimate of the average fraction of stover that could be removed with no-till cropping, enough to produce at least 5 billion gallons of ethanol at current conversion rates.

There is a wide range in potential GHG emissions offsets, dependent on weather, soil characteristics, type of application, agronomic practices and other factors, but the potential for mitigation is substantial.

The fossil fuel offset estimate, 50 to 70 million metric tons of carbon dioxide equivalent ($MMTCO_2$), is based on E85 fuel, a blend of 85 percent ethanol with 15 percent gasoline. The effective benefit is 0.6 to 0.9 $MMTCO_2$ mitigated per ton of corn stover processed. E85 from corn stover is estimated to reduce greenhouse gases 64 percent compared to gasoline.[35]

Changing to no-till cropping can further mitigate GHG emissions by 40 to 80 million metric tons of CO_2 equivalent annually by increasing carbon in the soil, reducing nitrogen fertilizer needs and reducing the intensity of field operations. Collecting excess stover only from no-till fields is recommended.

Figure 5: Fossil Energy Requirements: One mile driven on E85 fuel



Source: John Sheehan, Andy Aden, Keith Paustian, Kendrick Killian, John Brenner, Marie Walsh and Richard Nelson, "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol." J. Ind. Ecology, 7:3-4, 117-146 (Summer/Fall 2003).

Tilling causes loss of soil carbon. If too much stover is removed or a cover crop is not planted, soil carbon can be depleted.

Soil carbon is thought to be more strongly impacted by belowground residues (i.e. roots) than aboveground residue. Studies at the National Soil Tilth Laboratory show 80 percent or more of the surface material is lost as CO_2 within months and three times the amount of soil organic matter (SOM) comes from roots compared to surface material.[36] With biorefineries, the excess surface residues are converted into fuels that power vehicles before entering the atmosphere as CO_2. Moving to no-till avoids the loss of SOM from plowing.

Including cover crops in the rotation helps ensure that soil quality is maintained and most likely increased before reaching a new equilibrium in 30 to 50 years. Cover crops can build soil carbon, reduce erosion, help control weeds and may reduce chemical inputs by controlling weeds and retaining nitrogen in the root system over the winter. However, cover crops also require a higher level of management. Selecting the appropriate cover crop to fit in the rotation can reduce cost, possibly add a third cash crop and build soil quality, especially organic material, improving yields over time. However, if not well managed, cover crops can reduce yields.[37]

Reduced nitrogen (N) fertilizer use is also possible with no-till cropping, depending on crop rotation. Soil microbes desire a 10-to-1 ratio of carbon to nitrogen for digesting residue. Since the carbon-to-nitrogen ratio of straw and stover varies between 40 to 1 and 70 to 1, nitrogen fertilizer addition equivalent to 1 percent of residue is typically recommended to avoid denitrification of the next crop. When residues are removed, a more ideal ratio is maintained naturally.

For 150-bushels-per-acre corn yield, 70 pounds of nitrogen fertilizer may be avoided per acre if no residue is plowed under. In addition to cost savings,

35 Levelton Engineering Ltd. and (S&T)2 Consultants Inc., "Assessment of Net Emissions of Greenhouse Gases From Ethanol-Blended Gasoline in Canada: Lignocellulosic Feedstocks," Report to Agriculture and Agri-Food Canada. (Ottawa, Ontario, Agriculture and Agri-Food Canada, January 2000.) http://www.tc.gc.ca/programs/Environment/climatechange/docs/biomass/JanFinalBiomassReport.htm.

36 Cambardella and Gale, 2000. D.C. Reicosky, et al., 1995.

37 Sustainable Agriculture Network, 2001.

environmental benefits of reduced nitrogen fertilizer use include reduced run-off to streams and groundwater and reduced emissions of nitrous oxide (N_2O), a potent greenhouse gas. Nitrous oxide emissions range from 0.2 to 3.5 pounds of N_2O per 100 pounds of fertilizer applied.[38]

Since N_2O has 310 times the heat absorbance of CO_2, the resulting GHG offset is 0.5 to 9.9 metric tons CO_2 equivalent per ton of nitrogen fertilizer application. For 30 percent of the corn stover used as feedstock, the nitrogen fertilizer reduction is 800,000 tons, for a GHG gas reduction between 1 and 10 $MMTCO_2$.

Recent work suggests that for all corn cultivation systems across the Corn Belt, nitrous oxide generated by soil microbes may be the dominant greenhouse gas emission. Cover crops cut nitrous oxide emissions by up to a factor of 10. Combining cover crops with residue removal further reduced emissions.[39]

Combined, these greenhouse gas benefits would more than offset the net growth in U.S. emissions from all sectors of the economy in 2004.[40]

Global markets established to trade greenhouse gas emissions are now beginning to recognize no-till cropping as a legitimate tool for reducing atmospheric greenhouse gas concentrations. The Chicago Climate Exchange (CCX), a voluntary greenhouse gas trading market, allows farmers to sell the climate benefits of their cropping practice to industries wishing to offset their emissions. The Exchange offers farmers a conservative 0.5 metric ton per acre "exchange soil offset" credit for no-till operations, which translates to roughly $1 per acre at current CCX credit prices of $1.65 to $2.00 per metric ton CO_2. The Iowa Farm Bureau and other regional growers associations have organized farmers to collectively sell their credits on the CCX market.

In European markets, where mandatory limits on greenhouse gas emissions exist, carbon credit prices have ranged between $10 and $30 per metric ton CO_2, suggesting that if mandatory greenhouse gas emissions limits are established in the United States, benefits to farmers of no-till adoption could exceed $10 per acre, further driving the transition to no-till.

38 "Preparing U.S. Agriculture for Global Climate Change," Task Force Report 119. (Ames, Iowa, Council for Agricultural Science and Technology, 1992.)

39 Bruce Dale, Michigan Statue University, unpublished.

40 U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004", (Washington, D.C., U.S. EPA, April 2006). http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html.

CONCLUSION

Higher and more unstable prices of petroleum and natural gas, along with the desire to produce more energy domestically, are making agricultural feedstocks a more attractive alternative for the transportation fuels, chemicals, and plastics industries. With ongoing advances in both agricultural and industrial biotechnology, the economics are improving for these industries to switch from petrochemical to agricultural feedstocks. Governmental and international policies to reduce GHG emissions will add further economic incentives for biomass utilization as they develop.

Issues surrounding harvest, storage and transportation of feedstock supply need to be given significantly more attention if biomass is to serve as a sustainable platform for this industrial shift. Providing biomass feedstocks in sufficient and steady quantities to a biorefinery will require sustainable production and harvest practices as well as improved methods for delivery to the processor from the field.

In the near to mid term, crop residues are most likely to be the feedstock of choice for biorefineries. Improved agronomic systems such as no-till cropping with more crop residue removal can be implemented while also maintaining soil quality. The development of biorefineries, providing a market for crop residues, will provide economic incentives to farmers to adopt no-till cropping methods.

There are significant environmental benefits that can be gained from the switch to agricultural feedstocks from petroleum feedstocks for the transportation and chemical industries. Farmers who supply agricultural feedstocks to these industries could also benefit from a carbon credit system by switching to no-till cropping methods.

Coordinated governmental agriculture and energy policies are needed to encourage the growth of the biorefinery industry and facilitate the sustainable production of agricultural feedstock supplies. The 2007 Farm Bill may provide such an opportunity.

POLICY RECOMMENDATIONS

As a result of research for this report, several colloquies sponsored by federal agencies, and BIO workshops, BIO's Industrial and Environmental Section has developed a menu of recommendations that may help facilitate development of the infrastructure necessary for sustainable production and collection of cellulosic agricultural feedstocks and achieve the DOE goal of 30 percent displacement of petroleum with renewable biobased feedstocks by 2030. Congress should consider implementing the following policy measures in the 2007 Farm Bill:

- Fund research and development and provide incentives for the development of one-pass harvesting equipment and other new harvesting equipment for collection of cellulosic agricultural feedstocks;
- Develop and make available simple-to-use soil carbon computer models to allow individual farmers to compute how much crop residue can be collected without degrading soil quality;
- Provide support to farmers to assist with the transition to no-till cropping for biomass production;
- Provide incentives for the development and expansion of short line and regional rail networks for transport of cellulosic feedstocks;
- Fund regional demonstration projects to streamline the collection, transport and storage of cellulosic feedstocks;
- Develop a system to monetize greenhouse gas credits generated by production of ethanol and other products from agricultural feedstocks; and
- Fund programs to help farmers identify and grow the most suitable crops for both food production and cellulosic biomass production.

Cellulosic biomass from agricultural residues represents a highly promising new source of feedstock material for the production of ethanol, renewable chemicals and a range of commercial products. Residues from existing crops can greatly expand current production. American farmers are poised to deliver.

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