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SunGrant INITIATIVE

REGIONAL FEEDSTOCK PARTNERSHIP SUMMARY REPORT

Enabling the Billion-Ton Vision

July 2016

Regional Feedstock Partnership Summary Report:

Enabling the Billion-Ton Vision

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Bioenergy Technologies Office

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Availability

This report is available at bioenergy.inl.gov and bioenergy.energy.gov. Additionally, it is available, along with supporting documentation, data, and analysis tools on the Bioenergy Knowledge Discovery Framework at bioenergykdf.net and www.sungrant.org.

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Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office, Idaho National Laboratory, and the Sun Grant Initiative provide access to information and publications on biomass availability and other topics at the following websites:

energy.gov
eere.energy.gov
bioenergy.energy.gov
bioenergy.inl.gov
sungrant.org
www.anl.gov/energy-systems/project/bioenergy-landscapes
web.ornl.gov/sci/ees/cbes/

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Image courtesy of Chris Morgan, Idaho National Laboratory

This report describes the accomplishments of the Sun Grant Regional Feedstock Partnership (referred to as the Partnership) and represents the collective work of hundreds of individual contributors over 7 consecutive years. The comprehensive, long-term data that were required to answer questions about potentially sustainable biomass feedstock availability required dedicated and focused participation of coordinated teams from across the country.

The authors would like to acknowledge the support of the U.S. Department of Energy's Bioenergy Technologies Office (formerly the Office of the Biomass Program),[1] without which this work would not have been possible. In particular, we would like to appreciatively acknowledge the valuable contributions of John E. Ferrell, who provided visionary leadership in recognizing the criticality of a sustainable, reliable, economical biomass feedstock supply system to the commercialization of a viable biofuels industry. Mr. Ferrell was also instrumental in the formation and organization of the Partnership, which is an interagency public/private partnership for developing and deploying energy crop production and exploring the underlying data and assumptions regarding crop yield and sustainability that support the *Billion-Ton Study* analysis.

The Partnership is composed of representatives from a number of land grant universities organized under the Sun Grant Initiative, the U.S. Department of Energy, the U.S. Department of Agriculture, and industry. This document summarizes the accomplishments of the Partnership throughout the period of 2008 through 2014. It captures the progress made in validating assumptions regarding crop yields in the *Billion-Ton Study* and informing and revising the assumptions in the *U.S. Billion-Ton Update* and the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*, and in advancing biomass feedstock research and development.

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The Sun Grant Initiative is a national network of land-grant universities and federally funded laboratories working together to further establish a biobased economy. These institutes are at the forefront of research and innovation involving bioenergy and biofuels production. They have the history, technology, and resources available to lead the nation towards a renewable, sustainable, domestic energy industry. Sun Grant Centers are also charged with reviving America's farming communities by placing an emphasis on rural economic development through the production of biobased renewable energy feedstocks. Learn more at www.sungrant.org.

A full listing of all Regional Feedstock Partnership publications, presentations, reports, and other information outputs through 2015 can be found in appendix B (available online at energy.gov/eere/bioenergy/downloads/regional-feedstock-partnership-report and www.sungrant.org/News+and+Events/Regional+Feedstock+Partnership+Bibliography.htm). Appendix A is also available online through this energy.gov link.

Table of Contents

List of Figures

List of Tables

Executive Summary

Image courtesy of Douglas Karlen, Agricultural Research Service, U.S. Department of Agriculture.

U.S. Department of Energy/Sun Grant Initiative Regional Feedstock Partnership

A multi-institutional collaboration that was established to address issues associated with the development of a sustainable and projectable supply of cellulosic feedstocks in the United States in the future

The U.S. Department of Energy (DOE) and the Sun Grant Initiative established the Regional Feedstock Partnership (referred to as the Partnership[2]) to address information gaps associated with enabling the vision of a sustainable, reliable, billion-ton U.S. bioenergy industry by the year 2030 (i.e., the Billion-Ton Vision). Over the past 7 years (2008–2014), the Partnership has been successful at advancing the biomass feedstock production industry in the United States, with the following notable accomplishments:

- Validated many assumptions relating to yield potential and crop sustainability in the 2005 DOE report titled *The Technical Feasibility of a Billion-Ton Annual Supply* (commonly referred to as the *Billion-Ton Study*) (Perlack et al. 2005), and in the *U.S. Billion-Ton Update* (DOE 2011). The validation of these assumptions supports the conclusion that yield expectations that underpin the Billion-Ton projections are achievable (table ES-1).
- Provided information for the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (*BT16*) (DOE 2016a).
- Improved our understanding of the potential commercial use of many feedstocks for bioenergy, including corn stover, energy-

[2] More information is available at www.sungrant.org/Feedstock+Partnerships/.

cane, sweet and biomass sorghum varieties, switchgrass, *Miscanthus x giganteus* (i.e., Giant Miscanthus, hereafter "miscanthus"), Conservation Reserve Program (CRP) mixed perennial grasses, willow, and poplar.

- Demonstrated the production of herbaceous and woody feedstocks across a wide geography over 5–7 consecutive growing seasons (fig. ES-1).
- Provided yield potential and sustainability data that are necessary to support development and construction of at least three U.S.-based lignocellulosic biofuel refineries that rely on corn stover as a feedstock.
- Supported undergraduate, graduate, and postdoctoral education opportunities through demonstration sites, curricula, and thesis work in preparation for careers in the emerging fields of plant breeding, biomass production, feedstock supply logistics, and biomass conversion processes.

The *Billion-Ton Study* identifies the technical potential to expand domestic biomass production to offset up to 30% of U.S. petroleum consumption,[3] while continuing to meet demands for food, feed, fiber, and export. This study verifies for the biofuels and chemical industries that a real and substantial resource base could justify the significant investment needed to develop robust conversion technologies and commercial-scale facilities. DOE and the Sun Grant Initiative established the Partnership to demonstrate and validate the underlying assumptions underpinning the Billion-Ton Vision to supply a sustainable and reliable source of lignocellulosic feedstock to a large-scale bioenergy industry.

The following are specific examples of highly impactful outcomes from Partnership efforts:

- Development of comprehensive national and regional yield potential estimates for all species evaluated in the Partnership.
- Quantification of specific sustainable levels of corn stover harvest for use in commercial lignocellulosic biorefineries
- Assembly and conservation of a poplar germplasm collection that contains more than 20,000 clones, thus preserving valuable and irreplaceable germplasm for use in breeding programs. New clones resulting from crosses made using this germplasm collection have resulted in significantly improved cultivars that could be scaled up and deployed.
- Demonstration of multi-year yield durability of biomass sorghum, switchgrass, miscanthus, energycane, CRP mixed perennial grasses, poplar, and willow through enhanced agronomic practices and genetic evaluation
- Validation of improved yields across wide geography in new varieties/cultivars of biomass sorghum, energycane, hybrid poplars, and shrub willows.
- Demonstration of the increased winter cold tolerance of new energycane varieties relative to sugarcane varieties.

Ongoing work through the Partnership continues to further validate and refine assumptions made in the *Billion-Ton Study* and subsequent updates,

[3] Compared to U.S. petroleum consumption in 2005.

increasing the knowledge base for stakeholders within the bioenergy community. This validated knowledge base is essential because significant investment is required to (1) develop and expand bioenergy crops and agricultural residues to bring them to a commercial-scale market and (2) to build the necessary refineries and other facilities that will convert these crops into energy, fuels, and other useful products. Because of the information gained through the Partnership, many of the projections set forth in the *Billion-Ton Study* that were once thought by many to be overly optimistic are being shown to be reasonably realistic.

The Partnership legacy is far-reaching and includes a national resource of scientific and agronomic information, capabilities, and infrastructure, and a vast array of genetic resources in the form of germplasm collections for poplar and willow. Many of the bioenergy crops investigated by the Partnership were significantly advanced along the lengthy crop development pathway and are very close to being commercially available and able to contribute biomass to support the Billion-Ton Vision. For more information regarding experimental details, please refer to online appendix A.

This report discusses the accomplishments of the Partnership, with references to accompanying scientific publications. These accomplishments include advances in sustainable feedstock production, feedstock yield, yield stability and stand persistence, energy crop commercialization readiness, information transfer, assessment of the economic impacts of achieving the Billion-Ton Vision, and the impact of feedstock species and environment conditions on feedstock quality characteristics.

U.S. Department of Energy/Sun Grant Initiative Regional Feedstock Partnership

A collaboration that was established to address issues associated with the development of a sustainable and projectable supply of cellulosic feedstocks in the United States

1. Introduction

The U.S. Department of Energy (DOE) and the Sun Grant Initiative established the Regional Feedstock Partnership (referred to as the Partnership[1]) to address information gaps associated with enabling the vision of a sustainable, reliable, billion-ton U.S. bioenergy industry by the year 2030 (i.e., the Billion-Ton Vision). Over the past 7 years (2008 through 2014), the Partnership has successfully advanced the biomass feedstock production industry in the United States, with the following notable accomplishments:

- Validated many assumptions relating to yield potential and crop sustainability in the report *The Technical Feasibility of a Billion-Ton Annual Supply* (commonly referred to as the *Billion-Ton Study*) (Perlack et al. 2005), and in the *U.S. Billion-Ton Update* (DOE 2011). These assumptions support the conclusion that yield expectations for the Billion-Ton projections are achievable.
- Provided information necessary for the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (DOE 2016a).
- Accelerated the progress of many bioenergy feedstocks toward commercialization, including corn stover, energycane, sweet and biomass sorghum varieties, switchgrass, *Miscanthus x giganteus* (i.e., Giant Miscanthus, or miscanthus), Conservation Reserve Program (CRP) mixed perennial grasses, willow, and poplar.
- Demonstrated the production of herbaceous and woody feedstocks across wide geography over 5–7 consecutive growing seasons.
- Provided yield potential and sustainability data that are necessary to support development and construction of several U.S.-based lignocellulosic biofuel refineries.
- Supported undergraduate, graduate, and postdoctoral education opportunities through demonstration sites, curricula, and thesis work in preparation for careers in the emerging fields of biomass production, logistics, and conversion.

1.1 Validating, Refining, and Enabling the Billion-Ton Vision

The *Billion-Ton Study* identifies the technical potential to expand domestic biomass production to offset up to 30% of U.S. petroleum consumption, while continuing to meet demands for food, feed,

[1] More information is available at www.sungrant.org/Feedstock+Partnerships/.

fiber, and export.[2] This study verifies for the biofuels and chemical industries that a real and substantial resource base could justify the significant investment needed to develop robust conversion technologies and commercial-scale facilities (Perlack et al. 2005). DOE and the Sun Grant Initiative established the Partnership to demonstrate and validate the underlying assumptions underpinning the Billion-Ton Vision to supply a sustainable and reliable source of lignocellulosic feedstock to a large-scale bioenergy industry.

Ongoing work through the Partnership continues to further validate and refine assumptions made in the *Billion-Ton Study* and subsequent updates by increasing the knowledge base for stakeholders within the bioenergy community.

The following are specific examples of highly impactful outcomes from Partnership efforts:

- Development of comprehensive national and regional yield potential estimates for all species evaluated in the Partnership.
- Quantification of specific sustainable levels of corn stover harvest for use in commercial lignocellulosic biorefineries.
- Assembly and conservation of a poplar germplasm collection that contains more than 20,000 clones, thus preserving valuable and irreplaceable germplasm for use in breeding programs. New clones resulting from crosses made using this germplasm collection have resulted in significantly improved cultivars that could be scaled up and deployed.
- Demonstration of multi-year yield durability of biomass sorghum, switchgrass, Giant Miscanthus, energycane, CRP mixed perennial grasses, poplar, and willow through diverse agronomic practices and genetic evaluation.
- Validation of improved yields across wide geography in new varieties/cultivars of biomass sorghum, energycane, hybrid poplars, and shrub willows.
- Demonstration of the increased winter cold tolerance of new energycane varieties relative to sugarcane varieties.

This validated knowledge base is essential because significant investment is required to (1) develop and expand bioenergy crops and agricultural residues to bring them to a commercial-scale market and (2) to build the necessary refineries and other facilities that will convert these crops into energy, fuels, and other useful products. Because of the information gained through the Partnership, many of the projections set forth in the *Billion-Ton Study* that were once thought by many to be overly optimistic have now been shown to be mostly realistic, and private investments are being made in bioenergy feedstocks and lignocellulosic conversion facilities.

1.2 Identifying Data Gaps to Determine Vision Feasibility

Upon release of the *Billion-Ton Study,* multiple stakeholders set forth to determine the validity of its assumptions, in particular, the projection that by the year 2030, approximately 1.3 billion tons of cellulosic biomass could be available annually in the United States for production of liquid

[2] Compared to U.S. petroleum consumption in 2005.

fuels, chemicals, and power. A U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) assessment said the *Billion-Ton Study* set "bold, optimistic projections" and "lofty target(s)" (Wilhelm et al. 2006). Questions arose about the agriculture industry's ability to increase yields and remove agricultural residues (such as corn stover) without reducing the productive capacity of agricultural lands. Other questions arose about the likelihood that new practices would be adopted to support such high annual biomass production. Recognizing the magnitude of the effort that would be required to achieve such high production levels, the USDA-ARS assessment of the *Billion-Ton Study* provided the following skeptical conclusions (Wilhelm et al. 2006):

- Regarding projected yield increase of 50% by 2030—"doubtful"
- Regarding the projected residue-to-grain ratio increase for soybean from 1.5:1 to 2.0:1—"achievable, but of doubtful use..."
- Regarding the assumption that no-till farming practices could be adopted universally—"doubtful."

The same USDA assessment noted the competing traditional uses for crop residues, including for erosion control, feed, bedding, and as a soil amendment. Removing too much corn stover, which comprise a significant portion of the biomass resource in the *Billion-Ton Study* estimates, would deplete soil carbon content, which is an important indicator of soil productivity.

A 2007 CAST Commentary (Fales et al. 2007) concluded that the estimates in the *Billion-Ton Study* needed to be verified and regionalized and that data were needed on an agro-ecoregion/soil resource basis. The same paper identified the need for sustainable biomass production systems that maintain or enhance soil fertility, productivity, and soil organic carbon.

The USDA-ARS assessment raised many valid questions that needed to be answered to ensure creation of a sustainable biofuels industry. USDA-ARS and others understood the systemic complexity of filling the data gap between the *Billion-Ton Study*'s projections and what was actually achievable in the field.

1.3 Formation of the Regional Feedstock Partnership

Recognizing an opportunity to leverage efforts, DOE's Bioenergy Technologies Office (BETO) collaborated with the Sun Grant Initiative (7 CFR §3430.1001) to form the Partnership to perform the fieldwork necessary to validate or modify the biomass feedstock availability assumptions in the *Billion-Ton Study*.

In 2006 and 2007, workshops were held in each of the five Sun Grant regions (i.e., Northeast, North Central, Southeast, South Central, and West) to address the unique regional capacity to contribute to the vision of sustainably producing one billion tons of biomass feedstock by the year 2030. The workshops brought together research, government, industry, and other interest groups to begin work on a common framework for advancing biomass production and use in their respective regions. The potential regional production of a diversity of biomass feedstock was evaluated, obstacles and knowledge gaps were considered, research needs were identified, and key activities of the Partnership were outlined.

To generate the needed information, the Partnership was organized around primary biomass sources, resulting in five highly integrated teams: (1) agricultural crop residues, (2) annual energy crops, (3) perennial grass crops, (4) CRP and mixed grasses, and (5) short-rotation woody crops. Where appropriate, these teams included regional experts from each Sun Grant Center and from USDA-ARS to capture subtle differences in management approaches, while maintaining the level of coordination needed for broader impact. To help translate new data into knowledge and transfer that knowledge to interested users, experts in Geographic Information Systems and outreach specialists were assembled as separate teams to capture the program's progress and disseminate it to the public.

1.4 The Partnership Field Trials

One recommendation from the 2006/2007 Partnership workshops was about the importance of conducting long-term field trials with corn stover and herbaceous and woody energy crops to validate the assumptions about the feedstock yield potential. This required (1) evaluation of conventional agricultural logistics processes suitable for bioenergy feedstock production and (2) crop development to increase the yields of new energy crops through breeding and selection and to establish best management practices for those crops.

The workshops also highlighted the need to incorporate southern pine as a source of biomass. While significant amounts of feedstock are generated as residue from ongoing forest industry operations, there is also interest in establishing management practices for southern pine as a woody energy crop. The Partnership was able to leverage work underway by consortia in the southern region to provide new insight into the potential of this key source of biomass in the South.

> The Partnership enabled the production of yield maps showing the average potential biomass production from 1981 to 2010 for various herbaceous perennials, annual crops, and woody species.

To date, Partnership field trials have provided yield and other information for key biomass feedstocks (i.e., corn stover, biomass sorghum, energycane, miscanthus, switchgrass, CRP mixed perennial grasses, willow, and poplar) across multiple years and in diverse environments across the United States (field trial locations are shown in fig. 1). Specifically, the Partnership field trials have accomplished the following:

- Established reliable criteria for the sustainable collection of agricultural residues (i.e., corn stover and some cereal residues).
- Defined the yield potential for some existing varieties of all tested herbaceous and woody biomass crop species.
- Contributed to the development of regional best management practices.
- Expanded understanding of genetic capabilities of diverse germplasm across a broad geographic range.

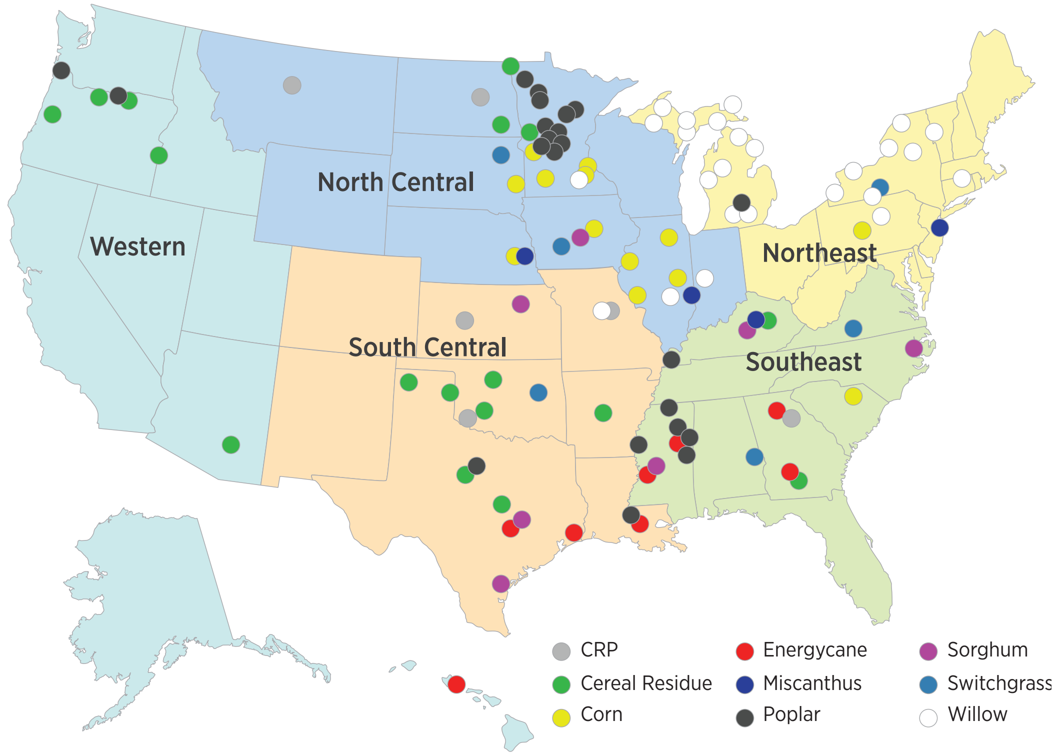

Figure 1 | The Partnership evaluated the yield potential and yield stability of several biomass feedstock crops across multiple Sun Grant regions to estimate the regional contribution toward expanded biomass production in the nation.*(Image Courtesy of the North Central Regional Sun Grant Center)*

The results generated from the Partnership had and continue to have a substantial impact on a wide variety of stakeholders across the bioenergy supply chain. For example, yield potential of various feedstock species across wide geographic gradients will be critical in biorefinery siting evaluations and in helping producers determine economic potential of adopting dedicated bioenergy feedstocks.

- The Partnership found that corn stover can be a sustainable feedstock for biorefineries.
- The Partnership validated the high-yield assumptions made in the *Billion-Ton Study and supported realization of the Billion-Ton Vision..*
- The Partnership validated and captured uncertainty in yield for bioenergy crops.

Farmers (including energy crop producers) and landowners have benefitted and will benefit further in the future from information that has been generated on a variety of different crops grown in various regions and from information on crop management practices that have been developed. Agriculture and natural resource professionals working for the local, state, and federal government have used Partnership data to develop best management and conservation practices that have become part of the guidelines and regulations for government agriculture programs. Companies such as POET-DSM have used

Figure 2 | The Partnership's contributions in creating methodologies and tools for determining the amount of corn stover that can be removed sustainably have enabled (a) siting of biorefineries in corn-growing areas and (b) negotiation of stover supply contracts with corn growers. *(Image courtesy of POET-DSM)*

this information to create new jobs in rural areas as new supply chains for biomass feedstocks, biofuels, and bioproducts have been developed. Policymakers are using information from the Partnership to project future sustainable production of biomass across the country and to develop guidelines and policies related to development of the bioenergy, biofuels, and bioproducts industries.

1.5 Feedstock Supply Systems for an Expanding Bioenergy Industry

The Partnership has been highly effective. It has provided the yield potential and sustainability data necessary to support feedstock supply systems that are enabling today's U.S.-based cellulosic biorefineries. For example, the Partnership was instrumental in addressing sustainability concerns that limit use

Figure 3 | Miscanthus in July 2013 (third growing season) in Gretna, Virginia. At most sites, miscanthus begins to provide plateau yields following the third growing season. Plots in this image received varying amounts of nitrogen fertilizer. At all sites in the Partnership study, miscanthus has not shown a yield response to nitrogen applications during the first 4 growth years, but some sites have shown yield increases in response to nitrogen application after 4 years of growth (Maughan 2012). The Partnership was set up to address these types of long-term questions. *(Image courtesy of John Fike, Virginia Tech)*

of corn stover as a feedstock, and they documented its role as a viable and significant bioenergy resource option for the United States (fig. 2).

The Partnership has also supported the advancement of the Billion-Ton Vision by making notable advances in developing energy crops toward commercialization (fig. 3), enhancing agronomic practices, and correlating management practices to feedstock quality. There is continued interest in the sustainable and renewable production of biofuels and chemicals amid concerns related to climate change, carbon sequestration in soils, and reliance on imported petroleum production for energy. The long-term nature of this research requires a concerted and continuous national effort (such as the Partnership) because yield stability and genetic effects under field conditions only become evident and relevant over multiple growing seasons.

1.6 Enabling the Billion-Ton Vision: Key Partnership Accomplishments

A critical accomplishment of the Partnership was alleviating concerns held by some that continuous residue removal was harmful to the land. The Partnership generated data and guidelines to support the use of corn stover as a sustainable feedstock for bioenergy production, therein easing the path for development of a cellulosic biofuels industry in the United States and moving toward realization of the Billion-Ton Vision.

More broadly, DOE investment in the Partnership has significantly advanced the knowledge base and public access to the data needed to begin answering many questions regarding sustainability and availability of biomass feedstock supplies and the production of bioenergy or other bioproducts. Rapid deployment of trans-disciplinary, multi-location research teams and leveraging of DOE resources with long-term USDA-ARS investments were very important accomplishments and enabled engineers, modelers, and agronomic scientists to develop effective and trusted communications.

Specifically, the *Billion-Ton Study* raised many scientific, technical, and economic concerns that were quickly addressed through development of the Partnership. Rapid DOE response concerns about soil organic matter raised by Partnership team members and populating the Bioenergy Knowledge Discovery Framework with field validation data were direct, high-impact outcomes of the Partnership.

The information and living genetic resources produced through the Partnership are essential for advancement of both commercial ventures and demonstration projects such as those assisted by USDA's Biomass Crop Assistance Program. For example, the Partnership's poplar research group has enabled continued successful commercial maintenance and/or expansion of poplar plantations (such as through GreenWood Resources in the Pacific Northwest), collaborations with the University of Minnesota and Michigan State University in the north central region and Mississippi State University and ArborGen, Inc. in the southeast, and the commercial Verso Paper operation in central Minnesota. Furthermore, genetic material in the willow program has been transferred into commercial nurseries and planted on more than 1,100 acres in upstate New York in a designated Biomass Crop Assistance Program project area.

The Partnership has developed into a national resource for scientific, agronomic, and genetic information. Work completed in the Partnership trials have helped move each of these bioenergy crops down the commercialization path, thus supporting the Billion-Ton Vision. For example, information obtained through the network of willow trials has helped Double A Willow, a commercial nursery in western New York that provides most of the planting stock for the willow biomass crop in North America, to scale up and commercialize new, high-yielding cultivars. Genetic resources evaluated or developed through the Partnership will require continued investment if they are to complete their transition from research organism to large-scale production crop.

2. Sustainable Harvest and Collection of Biomass Feedstocks

DOE investment in the Partnership has significantly advanced the scientific understanding and public access to data that are needed to assess the sustainability of biomass feedstock supplies and production of bioenergy or bioproducts. One of the findings crucial for securing private investments in the biofuel industry has been documentation that adequate quantities of corn stover can be collected to meet biofuel industry demands, while leaving enough residue on the field to protect and sustain the soil resource (Karlen et al. 2014; Johnson et al. 2014).

> Adequate quantities of stover can be collected in the Midwest as a feedstock to support projected biofuel industry demands, while leaving enough residue on the field to protect and sustain the soil resource.

This understanding has also led to development of sub-field, site-specific simulation models that have fostered development of venture capital companies. These models are helping change perceptions within the agricultural community to manage for return on investment rather than a simple field average yield goal. This potential paradigm shift also has been informed by the new insights the Partnership has gained regarding how the various feedstock sources might be integrated into a more holistic landscape-scale management vision that not only supports feedstock and bioenergy production but also helps demonstrate potential (1) important improvements in environmental quality, (2) economic growth, and (3) development in rural communities.

The initial DOE investment in the Partnership has advanced all three aspects of sustainability: (1) economic viability (e.g., proper nitrogen application rates to perennial grasses), (2) environmental quality (e.g., sustainable corn stover removal rates), and (3) social acceptability (e.g., through improved understanding by the public of the use of lignocellulosic feedstocks for bioenergy). However, development of viable biofuel and bioproduct industries is still in its infancy; additional joint public-private partnerships will be needed to fully and sustainably realize the Billion-Ton Vision.

2.1 Sustainable Biomass Production

Sustainability considerations apply to every operation along the feedstock supply chain. For example, Karlen and Rice (2015) identified quantifying the soil carbon (i.e., organic matter) and erosion response to alternative sources of cellulosic feedstock and their production strategies as critical soil degradation issues. Removing too much biomass from vulnerable soils can accelerate soil degradation, which will ultimately contribute to negative consequences such as disease and malnutrition (Sanchez and Swaminathan 2005). In addition, the loss of soil organic matter (SOM) results in degradation of soil structure that impairs water dynamics such as infiltration, retention, and release for plant growth.

Undoubtedly, sustainability is one of society's most complex challenges due to the multiple impacts it has on every sector of the bioenergy industry, particularly the productive capacity of land (Batie 2010). Because of this complexity, every decision regarding development and/or expansion of all cellulosic bioenergy industries must be made with consideration of the physical, chemical, biological, and social factors influencing sustainability at local, regional, national, and international scales (Karlen and Rice 2015). For example, excessive harvest of photosynthetic carbon and/or oxidation of soil carbon through excessive tillage will inevitably deplete SOM, reduce the soil's cation exchange capacity (this is a necessary reaction for the retention of plant-available nutrients), and result in soil degradation (fig. 4).

Every decision regarding development and/or expansion of all cellulosic bioenergy industries must be made with consideration of the physical, chemical, biological, and social factors influencing sustainability at local, regional, national, and international scales.

Another sustainability concern regarding biomass production and management is how these activities might affect water quality. In the Midwest, sustainability concerns over biomass harvest reflect not only an increased potential for impairment due to greater runoff and soil erosion (Cruse and Herndl 2009), but also due to percolation or leaching through the extensive subsurface drainage network that has been installed throughout this agricultural region (Dinnes et al. 2002).

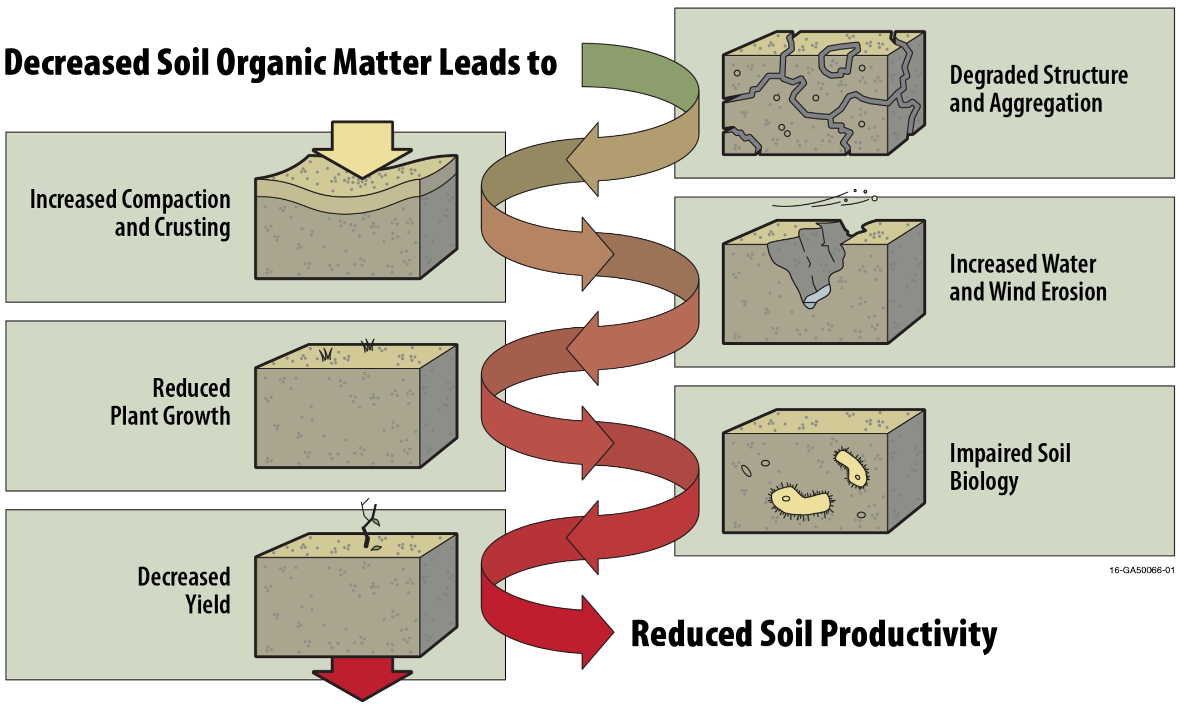

Figure 4 | A conceptual model of soil degradation, beginning with the loss of SOM due to excessive biomass harvest and/or tillage, erosion, grazing, or other poor soil and crop management decisions. *(Image courtesy of Doug Karlan [USDA-ARS], and Idaho National Laboratory)*

2.2 Primary Partnership Sustainability Discoveries

The Partnership evaluated several different sustainability indicators associated with harvesting biomass feedstocks over several years, including the effects of nitrogen fertilization, residue management, cropping sequence, effects on soil organic carbon (SOC) and particulate organic matter, greenhouse gas (GHG) emissions, and soil microbial community response. Results are summarized by crop in the following subsections. For additional details regarding sustainable harvest field trials and experimental conditions, please refer to online appendix A.

The Partnership recommendation for stover harvest: Corn stover should only be removed from areas where yields of No. 2 corn grain (i.e., 15.5% moisture) are greater than 175 bu acre^{-1}.

2.2.1 Corn Stover Sustainability Findings

Among the most critical questions influencing the sustainability of corn stover as a bioenergy feedstock are how, when, and what amount of stover needs to be left behind on the soil to minimize soil erosion and conserve SOC levels (at a minimum). Based on Partnership results, Johnson et al. (2014) concludes that striving to determine a minimum residue return rate is conceptually useful but can only be accomplished if field studies are of sufficient duration that a relationship between the rate of residue return and SOC change can be measured.

Assuming 175 bu acre^{-1} grain yield, about 50% of the stover harvest could be sustainable, especially if cover crops were used to provide additional protection against soil erosion.

Approximately one-third of the Partnership's corn stover sites did meet this criterion, primarily due to the ability of U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Renewable Energy Assessment Project (REAP) partners to leverage existing long-term studies (Johnson et al. 2014). Based on the available data, at least 2.85 ± 0.98 tons of stover acre^{-1} year^{-1} should be returned to the field to minimize soil erosion and conserve SOC levels. The large standard error emphasizes the high variability associated with these measurements and the critical need for basing actual management decisions on site-specific (i.e., sub-field) data.[3]

[3] These and other results from the corn stover research group were compiled in a special issue of *Bioenergy Research* in 2014 http://link.springer.com/journal/12155/7/2/page/1.

Figure 5 | A commercial-scale evaluation of the single-pass corn grain and stover harvest strategy in Minnesota *(Image courtesy of Stuart Birrell, Iowa State University).* Corn stover can be sustainably harvested provided corn grain yields are above 175 bu acre^{-1}. Note that the harvesting concept was developed from another funding source.

As a starting point for considering a sustainable stover harvest, the Partnership recommends that stover only be removed from areas where yields of No. 2 corn grain (i.e., 15.5% moisture) are greater than 175 bushels (bu) acre^{-1} (fig. 5). Stetson et al. (2012), with data from South Dakota, confirmed the importance of having high corn grain yields before considering stover harvest; for sites with lower yields, they found that stover harvest caused a reduction in SOC.

Osborne et al. (2014) concluded that in order to compensate for potential SOC declines, producers and policymakers should carefully consider the costs and benefits of using cover crops to offset potential soil quality degradation if stover is harvested. Similarly, Adler et al. (2015) concluded that if assuming a corn grain yield of 175 bu acre^{-1}, a partial (i.e., 50%) stover harvest could be sustainable in Pennsylvania, especially if cover crops were used to provide additional protection against soil erosion.

Villamil and Nafziger (2015) concluded that for Partnership research sites in Illinois, stover harvest tended to reduce phosphorous, potassium, and electrical conductivity levels in surface (0-inch to 6-inch depth) soils. Villamil et al. (2015) further established that even with no stover harvest, chisel plowing reduced SOC levels by 13% when compared to no-till management. Overall, their results indicated that stover harvest resulted in modest changes in soil properties under continuous corn production (in contrast to rotations of corn with soybean or cotton); however, the changes were generally smaller than those attributed to tillage or nitrogen-management treatments.

Partnership conclusion: Corn stover is a viable feedstock for sustainable bioenergy production in the U.S. Midwest if sufficient residue is returned and left on the soil surface to minimize soil erosion losses.

Jin et al. (2014) and Baker et al. (2014) evaluated GHG emissions at various Partnership research sites and reported that cumulative soil GHG emissions during the growing season varied widely across sites due to both management practices and yearly weather patterns. When combined across all sites and years, the average total GHG emissions (i.e., metric tons carbon dioxide [CO_2] equivalent per hectare) decreased by 5% ±1% due to stover harvest. In contrast, the site-specific response varied from -36% to 54%. Lower GHG emissions with stover harvest were attributed to reduced carbon and nitrogen inputs and subtle microclimate differences due to changes in soil cover.

Baker et al. (2014) also studied GHG emissions, and the cumulative data revealed no significant difference in N_2O emission as a function of stover harvest. CO_2 loss from the high-stover removal treatment, which averaged 3.2 tons acre^{-1} year^{-1} for the Partnership sites (Jin et al. 2014), was slightly lower than loss from the no stover-removal treatments. However, the difference in CO_2 loss from the soil between the high- and no-stover removal rates was less than the amount of carbon removed in the stover. The Partnership concluded that corn stover is a viable feedstock for sustainable bioenergy production in the U.S. Midwest, provided that sufficient residue is left on the soil surface to minimize soil erosion losses and maintain or increase SOM levels.

2.2.2 Biomass Sorghum Sustainability Findings

In the climates tested, Partnership studies found that GHG emissions from biomass sorghum crops occur year-round. While the most active period of GHG emissions in central Texas was typically during the growing season, the fallow period contributed to an appreciable amount of annual GHG emissions, possibly due to relatively mild fallow season temperatures and increased precipitation (Storlien et al. 2014). Although fallow season GHG fluxes are likely lower than those from the growing season, the milder, wetter conditions may also be conducive to sustaining significant GHG fluxes.

On the basis of soil respiration chamber measurements, Storlien et al. (2014) concluded that returning crop residues to the soil increased cumulative CO_2 emissions each year, presumably due to increased heterotrophic microbial activity. They also concluded that additional research is needed to identify optimal nitrogen and residue application rates that will result in high yields with minimal GHG emissions and no negative impacts on soil quality.

2.2.3 Switchgrass Sustainability Findings

Several factors were evaluated that could affect the sustainability of switchgrass as a potential feedstock for bioenergy production. The Partnership found that landscape position played a significant role in switchgrass productivity. Data were collected from areas of marginal land that were previously used for row crop production. Analysis of soil cores showed higher SOM and lower bulk densities than did eroded localized high spots on the land, which were termed "shoulder areas." Those two factors significantly correlate with switchgrass productivity; therefore, it is hoped that by establishing a perennial crop on shoulder positions, soil quality and productivity will gradually improve and potential negative environmental effects (such as nitrogen leaching and erosion from that landscape position) will be reduced.

The effects of nitrogen fertilizer and landscape position on CO_2 and methane (CH_4) emissions from a switchgrass field in the northern Great Plains were also quantified (fig. 6). Using the static chamber technique described by Parkin and Venterea (2012), Mbonimpa et al. (2015a) found that CO_2 emissions were 40% higher at the foot slope (i.e., localized low spots on the land) than shoulder positions (i.e., localized high spots), while CH_4 emissions were similar at both positions. Soil CO_2 and CH_4 emissions averaged over the sampling dates were not impacted by nitrogen application rates. Seasonal variations showed the highest CO_2 release in summer and fall, presumably due to warmer and moister soil conditions (Mbonimpa et al. 2015a). Lai et al. (2016) found that future projected CO_2 fluxes from switchgrass land under changing climate scenarios were not significantly different. Based on the DAYCENT simulation results (Parton et el. 1998), future CO_2 fluxes from switchgrass land will not significantly increase with increases in temperature; thus, long-term switchgrass production may help mitigate climate change impacts because of its improved benefits to the soil.

In a life-cycle analysis of energy use from switchgrass-derived ethanol, Mbonimpa et al. (2015b) demonstrated the importance of a proper nitrogen application rate. They confirmed that nitrogen rates above 50 lb N acre^{-1} yielded no increased biomass production benefits in South Dakota, while excessive nitrogen rates (i.e., >50 lb N acre^{-1}) increased (up to twofold) GHG emissions, volatile organic compounds, and criteria pollutants, primarily as a result of the nitrogen fertilizer production process.

Landscape topography also influenced life-cycle impacts. For example, switchgrass grown at the foot slope of fertilized plots led to higher biomass yield and lower GHG emissions, volatile organic compounds, and criteria pollutants in comparison with those at the shoulder position. Maintaining switchgrass for its maximum productive stand life (i.e., 10 to 20 years) further improves its energy and emissions benefits (Mbonimpa et al. 2015b).

Figure 6 | Analyzer control unit with solar panel power (*left*) and static chamber (*right*) of an automated soil CO_2 flux system in a switchgrass stand during July *(Image courtesy of Chang Oh Hong, South Dakota State University)*

Nitrogen use efficiency is an important factor in relation to both environmental and economic sustainability of biomass feedstock production systems. Increasing nitrogen-use efficiency by the crop helps reduce leaching of nitrates into groundwater and improves economic returns; therefore, the proper application rate for optimizing yield is essential. Owens et al. (2013) found that high amounts of initial soil nitrogen caused fertilizer nitrogen use to be low in switchgrass Partnership trials; however, high nitrogen use efficiency was observed at Partnership locations where initial soil nitrogen was low. Thus, site-specific nitrogen management strategies are critical for proper application of nitrogen.

2.2.4 Miscanthus Sustainability Findings

The Partnership performed studies on the effects of fertilization on GHG emissions for miscanthus. Behnke et al. (2012) evaluated the effects of three urea nitrogen fertilizer rates (i.e., 0, 54, and 107 lb N acre^{-1} year^{-1}) applied to a 1-year-old miscanthus crop on nitrous oxide (N_2O) and CO_2 emissions, nitrogen leaching, and biomass

> Site-specific nitrogen management strategies are critical for proper application of nitrogen and reduced environmental contamination.

yields. They found no significant yield response to nitrogen fertilizer in either 2009 or 2010; however, the amount of nitrogen in the harvested biomass in 2010 was significantly greater for both fertilizer treatments. N_2O emissions were not affected by the nitrogen fertilizer rate in 2009, but in 2010, they increased as fertilizer nitrogen rates increased. There also were no nitrate leaching differences between nitrogen fertilizer treatments at a depth of 20 inches in 2009; however, in 2010, there was significantly more nitrate as nitrogen (NO_3– N) leaching in the 107 lb N acre^{-1} (26 lb acre^{-1}) treatments than in the 0 lb N acre^{-1} (8 lb acre^{-1}) treatments. Davis et al. (2014) continued miscanthus nitrogen fertilizer evaluations by measuring the effects that the same three rates had on biomass production, SOM, and inorganic nitrogen leaching in Illinois, Kentucky, Nebraska, New Jersey, and Virginia. The study also continued measuring N_2O and CO_2 emissions at the Partnership Illinois site. Except for the Illinois site in 2012, there was no response to nitrogen fertilizer. Potentially mineralizable nitrogen in the soil surface layer (i.e., the upper 4 inches of soil) increased for all fertilizer treatments and sites, indicating that the SOM composition was altered after just four years of miscanthus production. Even though biomass yields were generally not significantly affected, the Partnership found that applying nitrogen did increase leaching and N_2O emissions. Further research is needed to determine when and at what rate nitrogen fertilizer should be applied to miscanthus. Early results indicate that it should not be within the first 4 years after establishing the crop.

CASE STUDY

Corn Stover: A Sustainable Feedstock for Energy Production

Regional Feedstock Partnership Research Collaboration Advances Bioenergy Production with Sustainable Corn Stover Harvest Guidelines

Between 2005 and 2015, corn was planted on an average of 88.9 million acres each year in the United States; therefore, corn stover was identified by the U.S. Environmental Protection Agency and many others as the primary initial feedstock for cellulosic bioenergy production. This led to the inclusion of corn stover in the Partnership, forming the corn stover research group, which is a highly successful collaboration among more than 50 scientists and engineers. Using new and ongoing, long-term USDA-ARS studies, the corn stover research group provided 239 site years of data from 36 replicated field experiments in seven different states between 2008 and 2012. Commercial hybrids were recommended for each site and were used to enable immediate application of the information by new biorefineries.

Data and results from the Partnership studies support use of corn stover as a sustainable feedstock for bioenergy production.

Significant outcomes of the Corn Stover Regional Partnership Research Group include the following:

- Generated data to support use of corn stover as a sustainable feedstock for bioenergy production
- Demonstrated that stover harvest strategies should be site, or even better, sub-field specific
- Developed a recommendation that corn stover be harvested routinely only if corn grain yields consistently averaged 175 bu acre^{-1} or more
- Quantified that harvesting an average of 1.7 tons acre^{-1} of corn stover would increase annual nitrogen, phosphorus, and potassium removal by 22, 2.4, and 28 lb acre^{-1}, respectively
- Demonstrated that corn stover harvest could help alleviate subsequent crop residue management problems, such as nitrogen immobilization and cool soil temperatures the next spring if grain yields are consistently greater than 200 bu acre^{-1}
- Demonstrated that a moderate stover harvest could facilitate adoption of no-till crop production practices and reduce tillage intensity, thereby reducing carbon emissions from soil

CASE STUDY (continued)

Corn Stover: A Sustainable Feedstock for Energy Production

- Demonstrated across a 10-year period that soil particulate organic matter could be maintained when average corn grain yields were less than 175 bu $acre^{-1}$
- Quantified that the reduction in soil CO_2 emission associated with corn stover harvest was much lower than the amount of carbon removed with the stover, indicating that routine soil sampling should be used to monitor SOM changes at stover harvest sites
- Documented that harvesting above-ground biomass could supply between 12 and 68 gigajoules per acre (GJ $acre^{-1}$) of energy per year, depending on annual rainfall and biomass yield.

Overall, the multi-stakeholder collaboration that resulted from the corn stover research group work significantly advanced the economic, environmental, and social sustainability of cellulosic bioenergy production. Three companies (Abengoa, DuPont Cellulosic Ethanol, and POET-DSM) were among the private sector partners contributing to this research group. All of the companies used the information generated through this collaborative research to develop plans for harvesting corn stover from almost 300,000 acres in the Midwestern United States during the fall of 2015.

The success of this research group has helped ensure cellulosic-derived biofuels are here to stay. It is critical that collaborative research be continued to ensure soil and water conservation information needs are met, such that sustainable liquid fuel supplies and other bioproducts can be developed without having negative consequences on the ecosystem.

3. Advances in Understanding Feedstock, Yield Stability, and Crop Stand Persistence

The Partnership enabled the first nationally coordinated field-scale bioenergy feedstock research effort, which spanned from 2007 through 2014. Field trials of this length and nature are essentially nonexistent in the peer-reviewed scientific literature; however, because of DOE investment, the Partnership was able to evaluate potential energy feedstocks in periods of significant drought (e.g., 2012 when much of the nation experienced drought conditions) and periods when flooding occurred in specific regions. The coordinated research effort included diverse species (including annual, perennial, herbaceous, and woody feedstocks), cultivars and experimental lines, geographic locations, soil types, and research treatments (e.g., nutrient additions, harvest timing, and genetics).

The time invested and diversity of species and treatments included in the Partnership studies helped define factors that influence the yield, yield stability, and stand persistence of a variety of bioenergy crops species. Crop yield refers to the total mass of harvested biomass produced on a given area of land over a specific time period. Yield stability refers to the ability of the crop to produce good yields under a wide variety of environmental conditions at the same location. Stand persistence describes the ability of that perennial crop stand (i.e., a single planting) to maintain adequate productivity over time. Most importantly, the Partnership provided critical ground truth data to help validate projections of the nation's ability to produce at least one billion tons of cellulosic feedstocks annually by the year 2030. For corn and biomass sorghum, data representing more than 200 site-years over five consecutive growing seasons were generated that enabled a comprehensive understanding of both temporal and spatial yield variability in these annual crops. For the perennial feedstocks (e.g., herbaceous and woody species), accumulating 5 or more years of data is rarely possible due to funding and other limitations; however, this was accomplished through the Partnership for six perennial crops. In fact, the number of years included in the Partner-

> Partnership data continues to inform BETO-funded resource assessments, such as the *2016 Billion-Ton Report,* which is DOE's most recent outlook for lignocellulosic feedstock that could be available for future energy production.

> The Partnership provided critical ground truth data to help validate projections of the nation's ability to produce at least one billion tons of cellulosic feedstocks annually by the year 2030.

ship has provided critical information regarding stand persistence over time for these key perennial species.

The valuable yield information collected through the Partnership has been used in BETO-funded resource assessments, such as the just-released *2016 Billion-Ton Report*, which is DOE's most recent outlook for lignocellulosic feedstock that could be available for future energy production. The scale of work completed in the Partnership was only possible because of DOE's investment and the long-term commitment to a large and diverse team of scientists and advisors. These resource assessments help reduce risk to both biomass producers and biorefinery investors by establishing an estimate of the potentially obtainable biomass yields at the county level of resolution. For more information related to feedstock yield and persistence field trials, please refer to online appendix A.

3.1 Primary Partnership Discoveries on Yield, Yield Stability, and Stand Persistence

The Partnership has helped define and improve understanding of many of the key factors associated with variability in feedstock yield and persistence, such as variable weather patterns, soil nutrients and fertilizers, stand age, genetics, and geographic location. The average and range of crop harvested yield values over time and across wide geography are shown in table 1.

Table 1 | Baseline Yield Assumptions in the *U.S. Billion-Ton Update* and Range of Average and Actual Yields for Species Evaluated in Partnership Field Trials (yield results collected by the Partnership supported baseline yield assumptions used in the *U.S. Billion-Ton Update*)

Feedstock	*U.S. Billion-Ton Update* baseline yield assumptions (dry tons $acre^{-1}$ yr^{-1})	Average yield of partnership field trials (dry tons $acre^{-1}$ yr^{-1})	Yield range of partnership field trials (dry tons $acre^{-1}$ yr^{-1})
CRP (mixed perennial grasses)	N/A[a]	1.4	0.7–2.7[b]
Corn stover	1.7[c], 2.8[d]	--	1.7–3.4[e]
Energycane	9.0	11.6	7.8–14.2[f]
Miscanthus	5.7[g]	7.7	2.6–15.2[h]
Biomass sorghum	6.7	8.0	1.3–18.3[i]
Switchgrass	5.7[g]	3.5	1.1–7.4[j]
Poplar	5.3	5.0	3.5–7.0[k]
Willow	4.7	3.8	1.5–6.3[l]
Southern pine	N/A	N/A	3.3–8.5[m]

Source: DOE (2011).

[a] The *Billion-Ton Study* excluded CRP land as eligible for biomass production.

[b] See Anderson et al. (2016).

[c] National average yield at \$60 dry ton^{-1} or less in 2022 for reduced-till production.

[d] Same as above, but no-till production national average.

[e] Available corn stover is highly site specific, but 239 site-years of data from 36 Partnership locations indicate that with a sustained, average corn grain yield of 175 bu $acre^{-1}$, 1.7 tons $acre^{-1}$ of corn stover could be harvested without negatively affecting productivity or soil carbon levels. As corn grain yields increase to 250 bu $acre^{-1}$, the amount of available stover increases to 3.4 tons $acre^{-1}$. See also Karlen et al. (2014).

[f] Energycane yields are from eight sites from 2009 through 2014 are included in the average and range values. See also Baldwin et al. (2012) for detailed data from 2009 through 2010.

[g] Switchgrass and miscanthus are combined and modeled and reported together as perennial grasses.

[h] Miscanthus yields from five sites from 2009 through 2014 are included in the average and range values. See also Behnke et al. (2012) for detailed data from 2009 through 2010.

[i] Gill et al. (2014).

[j] Switchgrass yields from six sites (four with upland switchgrass and two with lowland switchgrass) from 2009 through 2014 are included in the average and range values and are combined across upland (23 site-years) and lowland (9 site-years) cultivars utilized at diverse environments across the U.S. Field Trial locations. See also Hong et al. (2014) for detailed data from 2009 through 2012.

[k] Poplar yields represent selected clones on a range of sites from northern climates (northern Minnesota) to humid southern climates (South, Mid-South alluvial sites). Additionally, an important result is the diversity of genetics developed through breeding supported by the Sun Grant program with significant opportunities to improve yield and yield stability through continued testing of this enhanced genetic set of materials. See also Berguson et al. (2012) for further information.

[l] Willow data represents first-rotation yields of the top five cultivars across a wide range of sites. Current recommendations are to plant multiple cultivars for commercial expansion of willow to maintain genetic diversity in a field and minimize risk associated with pests and diseases. Yields in a number of these trials have increased in the second rotation, particularly those with lower first-rotation yields. Those increases in yield in second or later rotations are not reflected in this information. See also Sleight et al. (2016) for further information.

[m] Southern pine was not included for the field trial studies; however, yield information was obtained from recent literature reports. The range of biomass yields reflects different sites and different levels of management intensity (Rials et al. 2014).

3.1.1 Weather Variability

As expected, weather variability, especially the timing and amount of precipitation, had the greatest effect on yield. This was easily identified as a key factor because none of the Partnership trials were irrigated. For example, although sorghum is grown across the South and Midwest, the lowest average yields were in the regions traditionally associated with lower rainfall (i.e., Texas and Kansas). Thus, while sorghum is quite tolerant of surviving periods of drought, the Partnership trial results indicate that the greatest yields occur in environments with consistently greater rainfall (Gill et al. 2014). Similarly, during 2012, miscanthus yields were very low due to a severe drought that impacted much of the study region; however, yields recovered at most sites in 2013 (Davis et al. 2014). This study reinforced the determination that miscanthus should be produced in the central United States, where annual precipitation averages at least 30 inches.

The Partnership trials also confirmed the correlation of rooting structure, weather variability, and yield. For example, due to their deep rooting structure, the established perennial crops were less affected by a 1-year drought than the more shallow-rooted annual crops, like corn and sorghum. On the other hand, inadequate precipitation in the seeding year twice resulted in unsuccessful establishment at one switchgrass Partnership location. Switchgrass production was similar in 2012 to other years at most locations despite widespread drought across significant parts of the country (Hong et al. 2014). In contrast, average removal rates for corn stover ranged widely from 1.7 to 3.2 tons acre^{-1}, with variability due to differences in growing conditions (e.g., rainfall and temperature patterns), field-specific lodging caused by severe wind storms, and/or yield loss due to drought or hail. For CRP mixed perennial grasses, the greatest impacts on seasonal biomass production were due to location-specific precipitation, because annual feedstock production was reduced by up to 80% when the growing season precipitation was less than 50% of the average over the prior 3-year period during 2008 through 2013 (Anderson et al. 2016). Drought conditions also negatively affected energycane yields at several locations during the trial (Baldwin et al. 2012). These examples demonstrate the impact of long-term investment in the Partnership.

3.1.2 Soil Nutrients and Fertilizers

Initial soil quality and the addition of nutrients were important management considerations for optimum feedstock yield and persistence in the Partnership studies. For example, switchgrass yield increased in response to added nitrogen in South Dakota and Virginia (averaging >60% yield over the control), reflecting the limited nitrogen in these marginal soils (Hong et al. 2014). Similarly, responses to nitrogen were limited in New York, Oklahoma, and Iowa for the first few years, but over time, switchgrass proved highly responsive to added nitrogen even on the very productive soils at the Iowa location. These observations could not have been made without the ability to maintain these plots for 5 years and more.

For miscanthus, many reports have indicated no productivity effects of nitrogen applications (Himken et al. 1997; Clifton-Brown et al. 2007;

Figure 7 | Harvesting warm-season species mixtures in North Dakota (*left, image courtesy of D. K. Lee, University of Illinois*) and cool-season species mixtures in Montana (*right, image courtesy of Chengci Chen, Montana State University*) on CRP land. Yields from CRP land were typically low; however, the crops responded very well to the addition of nitrogen fertilizer.

Christian et al. 2008; Maughan et al. 2012); however, the Partnership trials demonstrated that there are sites where yield can be enhanced by annual nitrogen applications, particularly after several years of growth. At the Illinois site, it was 50% to 60% more productive for miscanthus to receive annual applications of 54 lb N acre^{-1} than unfertilized plants in the fifth and sixth growing seasons after planting, respectively (Davis et al. 2014).

CRP mixed perennial grass yields clearly increased in response to nitrogen during most site-years; however, the added expense of nitrogen fertilizer may not always result in higher revenue (fig. 7) (Anderson et al. 2016). This demonstrates the critical nature of site-specific management of each feedstock both agronomically and economically.

3.1.3 Stand Age

Stand age refers to the length of time a perennial crop has been in production since it was planted. Long-term persistence of perennial crops may vary by species, site, and agronomic practices employed. For example, energycane yields declined significantly at the northernmost locations in the sixth year of production, something that would not have been detected had the Partnership efforts occurred over a shorter term. In fact, some decline in production coincides with observations in sugarcane fields, suggesting a maximum of 3 to 4 productive years before replanting is necessary.

Long-term stands have been essential for development of poplar clones as bioenergy crops because they require several years of growth before yield comparisons and disease susceptibility evaluations can be made and a first harvest can occur. For both poplar and willow, the Partnership enabled continued testing of existing legacy stands (some dating back to the 1990s) in addition to establishment of new stands with novel genetic material.

Many legacy stands might have been abandoned without investment from DOE through the Partnership. For example, Partnership investments in

> Willow yield was 20% to 70% higher in the second through sixth rotations compared to the first rotation. Selecting willow varieties based on data too early in the crop's lifecycle can lead to erroneous results.

willow provided the first long-term production data in the United States and showed that willow yield was 20% to 70% higher in the second through sixth rotations, as compared to the first rotation for trials with older cultivars (Volk et al. 2011). The pattern of how yield changes over several cycles with new cultivars is still being investigated to see if a reliable correlation exists, but results so far indicate it is strongly related to first rotation yields. However, in general, cultivars that have high first-cycle yields have a smaller percentage increase in yield in the second cycle.

In contrast, varieties with lower first-cycle yields have a larger percentage increase in yield in the second rotation (Sleight et al. 2016). In fact, long-term willow studies conducted through Partnership trials have shown that selecting high-yielding varieties based on yield data collected too early in the crop's life cycle can lead to erroneous conclusions. Selecting cultivars based on first harvest cycle yields from different sites can result in an 11% to 14% drop in expected yield, which can negatively impact the economics of this system (Sleight 2015).

> The Partnership has enabled the poplar breeding programs to generate more than 20,000 genetically unique clones, which will serve as the source of new genetic material for future evaluation.

3.1.4 Genetics

Using the best available parental germplasm to develop new cultivars is critical for continued improvement in yield, yield stability, and persistence. For poplar, testing of the newest clones is essential for (1) identifying the very small subset of unique clones from a larger collection that possesses the characteristics needed in operational biomass production and (2) selecting the next generation of elite parents for continued breeding efforts. The Partnership clone tests have helped identify clones best suited for further region or climate-specific yield tests. In addition, yields from the Partnership's fastest-growing tier of poplar clones range from 1.3 to 1.6 times that of currently available commercial clones.

The Partnership also has enabled poplar breeding programs in Minnesota and Oregon to generate more than 20,000 genetically unique clones, which will continue to benefit the biomass programs because these clones will serve as the source of new genetic material for future testing.

For willow, the Partnership realized yield increases associated with new cultivars that typically ranged from 15% to 25% better than commercial varieties, with some variation across sites (Volk et al. 2011). The broad range of sites included in this project has provided a valuable basis for understanding factors that influence willow production, including regional pest and disease pressures and the effects of diverse environments on the yield of specific genotypes (fig. 8).

For both switchgrass and biomass sorghum, new and higher-yielding varieties have become available since the Partnership was initiated (Gill et al. 2014). In fact, several companies have commer-

Figure 8 | Harvesting a 3-year-old willow in a yield trial in Tully, New York, in 2014 (*left, image courtesy of Tim Volk, SUNY ESF*) and flower of willow cultivar S365 in early spring in Tully, New York (*right, image courtesy of Ben Ballard, SUNY ESF*). Willow is one of the first plants on the landscape to flower and is potentially an important food source for pollinators in the early spring.

cialized biomass sorghum hybrids specifically for the energy market since the sorghum work was initiated in 2008 (Rooney 2014). The tractable genetics of sorghum coupled with established breeding systems have already allowed rapid advances to be made in the productivity of high biomass sorghum.

The Partnership tested five energycane genotypes for the ability to persist and produce good yields at latitudes from 30° to 33°N latitude, representing roughly 250 miles and two USDA hardiness zones (Baldwin et al. 2012). The five energycane genotypes included hybrids, those backcrossed to the cold-hardy parent, and those backcrossed to the cold-intolerant sugarcane parent. Those more closely related to the cold-hardy parent had woody stems and were lower in soluble carbohydrates in the expressed juice, while those backcrossed to sugarcane had a slower onset of growth in the north in spring and pithy stems with a greater concentration of sugars in their juice. These five genotypes were all included at each Partnership test location across the Southeast and in Hawaii. Increases in human population along the coast of Hawaii have pushed agricultural production up the slopes; thus, it was critical that this material be tested there. In addition, germplasm is needed that tolerates cooler, more temperate climates with lower winter low temperatures. All energycane genotypes survived at 33°N latitude, while sugarcane checks froze out the first winter. Yields of all genotypes were compromised the further north the site was located. Woody types (Ho 06-9001 and 9002) were hardier at the northern locations. Regardless of location, grand growth ceased the second to third week of September when mean temperature dropped below 30°C (85°F).

3.1.5 Geographic Location

It is well understood that location matters for all agricultural species and that the location interacts

Figure 9 | Energycane field trials in St. Gabriel, Louisiana (*left, image courtesy of Ed Richard,* USDA-ARS), Starkville, Mississippi (*middle, image courtesy of Brian Baldwin, Mississippi State University*), and Tifton, Georgia (*right, image courtesy of William [Bill] Anderson, USDA-ARS*), during mid-season

with the weather variables (i.e., precipitation and temperature). The Partnership trials enabled testing of many cultivars at highly diverse environmental locations. For example, energycane that was adapted for the humid south was tested in the south and in more northern environments around Athens, Georgia, and Starkville, Mississippi. The energycane germplasm tested in the Partnership trials not only demonstrated high production potential in the south (i.e., >20 dry tons acre^{-1} year^{-1}), but also substantial potential in the northern locations (i.e., 10 to 12 dry tons acre^{-1} year^{-1}) (fig. 9).

The Partnership also demonstrated that miscanthus is not well adapted to geographic areas receiving less than 30 inches of annual precipitation or to coarse-textured soils with limited water-holding capacity.

The Partnership documented that, when yields are high, corn stover harvest decisions must be site- or even subfield-specific (Bonner et al. 2014) to minimize crop residue management problems, while ensuring that adequate surface cover and carbon inputs are left in the field to (1) protect soil resources against wind- and/or water-induced erosion and (2) sustain or increase SOM. To effectively manage soil health, site-specific crop planning and management will be required to maximize yields and minimize risks. Tools have been developed to support the Partnership efforts, including those related to integrated landscape management and the PRISM Environmental Model (PRISM-EM; Halbleib et al. 2012), which are intended to help land managers maximize profits through optimizing yields and improving yield consistency.

Site-specific crop planning and management will be required to maximize yields and minimize risks.

3.2 Estimating National Yield Potential

One of the major objectives of the Partnership was to gain an understanding of the spatial distribution of the current and potential bioenergy feedstock resources across the country to better assess the feasibility of producing one billion tons of biomass annually by the year 2030. As described in previous sections, several key factors were identified that contribute to yield variability and impact the nation's technical ability to meet this goal.

Not all geographic regions could be represented by each species evaluated within the scope of the Partnership. Therefore, a critical task of the Partnership was to develop national yield potential maps for each species by using yield data collected in the Partnership field trials. While a rich data history exists in the United States for commercial crop yields (e.g., corn and sorghum), there was less production history for some of the other energy crops (e.g., switchgrass, miscanthus, energycane, poplar, and willow) that were evaluated by the Partnership. To improve understanding in areas where data were lacking, the Partnership was tasked with assessing the following:

1. Where can these new crops be raised successfully?
2. What kind of production can be expected within a given geographic region?

To accomplish the mapping exercise, face-to-face meetings were held between the PRISM modeling group and each Partnership species group. During these meetings, Partnership field trial results were discussed in detail to gain an understanding of the methods used to grow and manage the crop and how harvesting and yield data collection were performed. In some cases (e.g., switchgrass, southern pine), yield data were supplemented with peer-reviewed data collected outside the Partnership's efforts.

As a result of the Partnership's efforts and participation in these meetings, maps of average potential biomass production from 1981 to 2010 were produced using PRISM-EM for herbaceous perennial and annual crops (i.e., energycane, upland and lowland switchgrass, biomass sorghum, CRP mixed perennial grasses, and miscanthus; see fig. 10) and woody species (i.e., willow, poplar, and southern pine; see fig. 11). Using a common modeling and data collection framework in close collaboration with each species group, these maps provided a first look at the distribution of potential biomass production for the most nationally important energy crop species and have been used as the basis for economic analysis in the *2016 Billion-Ton Report*.

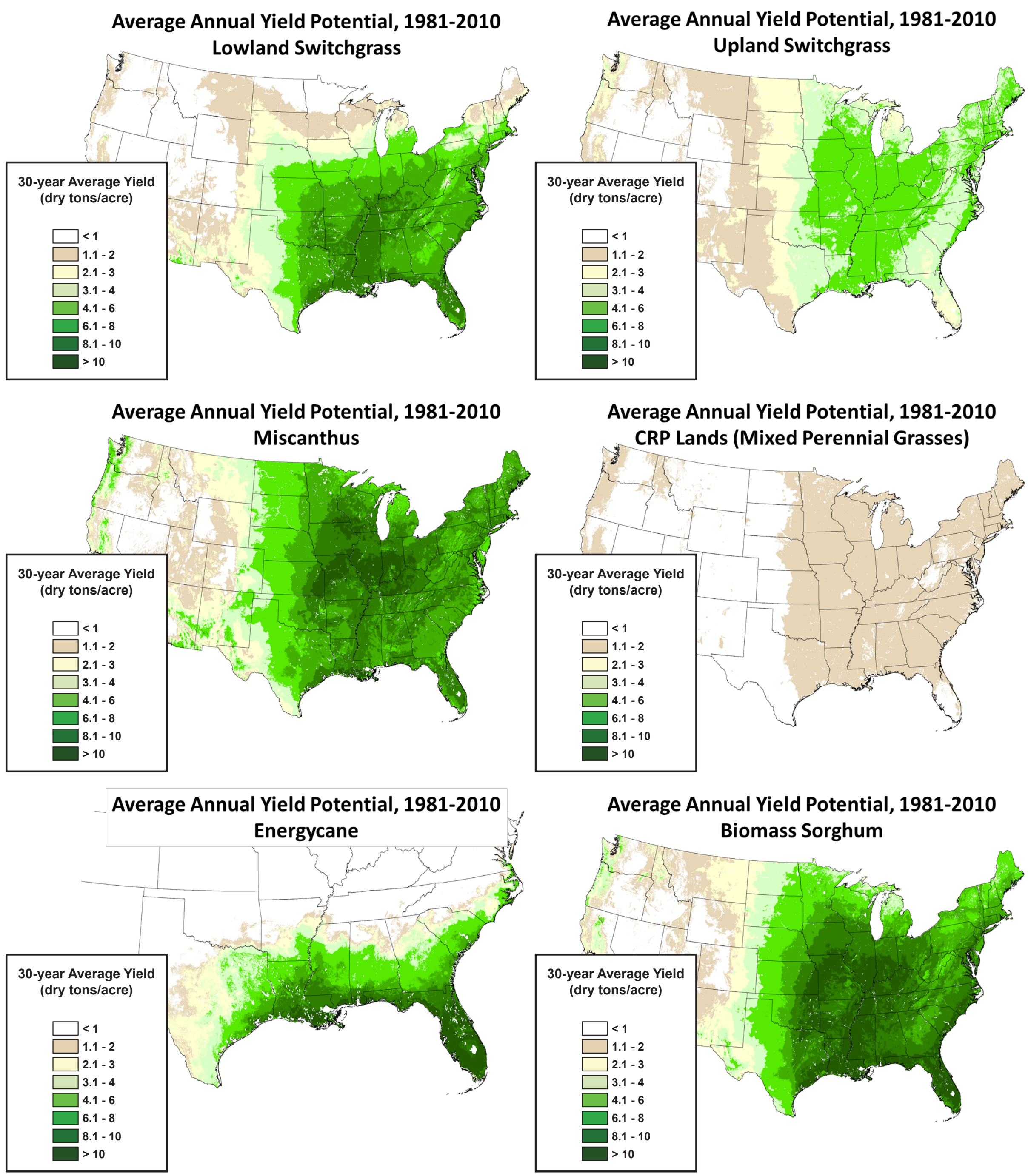

Figure 10 | Yield potential maps of perennial (i.e., switchgrass, miscanthus, CRP lands [mixed perennial grasses], and energycane) and annual (i.e., sorghum) herbaceous energy crops developed from Partnership field trials using PRISM-EM. Face-to-face meetings were held with each species research group and the PRISM EM modeling group to enhance information exchange between all partners. These maps represent the state of knowledge through the 2012 growing season. Work-to-map yield potential is ongoing, and the maps are being updated as more data are obtained. *(Figures courtesy of Christopher Daly and Michael Halbleib)*

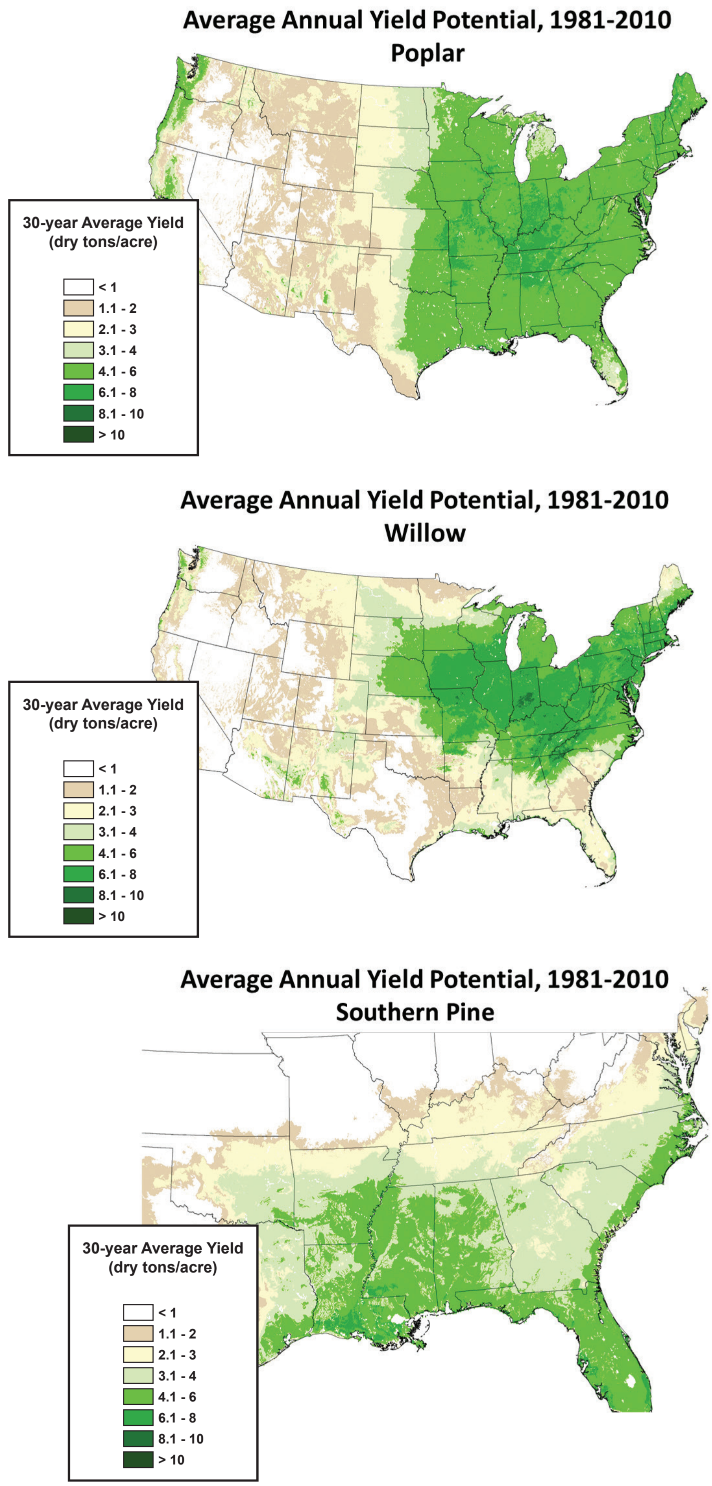

Figure 11 | Yield potential maps of woody energy crops (i.e., poplar, willow, and southern pine) developed from Partnership field trials and data collected previously by Partnership participants using PRISM-EM *(Figures courtesy of Christopher Daly and Michael Halbleib)*

4. Scale-Up of Energy Crops: Rapid Progress Toward Commercialization

To develop and deploy new plant varieties, the progression from laboratory experiment to full-scale commercial crop production requires a substantial investment of time and resources. Identification or development of the right cultivar requires a minimum of 8 years, with many requiring 10 to 15 years. Once the cultivar is in hand, suitable locations for large-scale production must be identified, and it again can take several years to expand the cultivation small yield trials to enough acreage to supply a meaningful harvest (fig. 12).

Social factors can also challenge commercialization of a new cultivar. It is difficult to persuade land owners to plant a new crop without an identified customer who has contracted to buy their harvest. It can be equally difficult to persuade a prospective customer to invest in costly infrastructure (e.g., a biorefinery) that depends on a new crop that (1) has yet to be planted and (2) has a performance over time that is not yet fully understood. Adding additional complexity, these new crops can require different agronomic practices, cropping systems, and logistic systems to handle the harvested feedstocks. As a final restriction, the feedstock must also meet the quality requirements of the available biorefinery conversion systems.

Figure 12 | Whole plot machine harvest of bioenergy sorghum grown in the Regional Biomass Feedstock Trial located on the Texas A&M AgriLife Research Farm near College Station, Texas, in 2010 *(Image courtesy of William Rooney, Texas A&M)*

> Long-term support for this project and the wide range of sites studied provides a realistic estimate of biomass production potential for several diverse bioenergy crops and thus, contributes to the realization of the Billion-Ton Vision by reducing some of the technical and social risks associated with feedstock production.

The Partnership has been successful in addressing obstacles that can limit the progression of bioenergy crops from the lab to full-scale production. The lack of reliable yield data over multiple years from a broad range of sites was one such obstacle for many energy crops. Prior to Partnership efforts, production data for many energy crops were based on results from small, experimental plots at very few locations over very short time periods (i.e., often 3 years or less). Mean yields from limited data sets were used for estimating land areas needed to supply end users, but this approach did not capture or represent the variability that occurs across the landscape. The long-term support of the Partnership, the wide geographic range of sites, and larger areas used for some trials provide a realistic estimate for several diverse bioenergy crops and, thus, contributes to realization of the Billion-Ton Vision by ground truthing real-world crop yields, which reduces some of the technical barriers and social risks associated with feedstock production. For more information on the results of scale-up field trials, please refer to online appendix A.

4.1 Risk Reduction for Corn Stover

One of the most important impacts of the Partnership has been to reduce the risk and uncertainty associated with production of biomass from a wide variety of energy crops and other feedstocks. For example, prior to the organization of the Partnership, there was a large degree of skepticism about the use of corn stover as a biofuel feedstock because of limited information on how its harvest would impact grain corn production and soil health over time. The expansive trials performed through the Partnership, across multiple sites, over a number of years (239 site years), have enabled the development of guidelines for sustainable corn stover removal rates.

This coordinated effort over five consecutive growing seasons also helped identify areas across the country that could sustain adequate corn stover harvesting to support the operation of a biorefinery. The results from this project have greatly reduced the risk and uncertainty related to use of corn stover as a feedstock in a biorefinery and have provided valuable input for POET-DSM, Abengoa, and DuPont Cellulosic Ethanol as they developed and implemented feedstock supply chains for their new biorefineries.

4.2 Expanded Data Sets for Energy Crops

At the start of this project, limited data were available for potential energy crops, including switchgrass, miscanthus, cereal residues, biomass sorghum, energycane, poplar, and willow. Most of the available data originated from small, scattered, uncoordinated trials that only lasted for a few years. This made it very difficult to understand the potential yield over multiple harvests, year-to-year variability, and a geographical range of production for many of these energy crops.

The Partnership coordinated and established an extensive network of trial sites and monitored them for at least 5 and up to 7 years. The resultant energy crop data sets cover a much broader range of climate and site conditions than previous studies, which provide both producers and end users with valuable information about specific locations and agronomic practices. In the case of energycane, poplar, willow, and biomass sorghum, varieties of each crop that may be most productive in a given region can be identified. For example, the poplar research group was able to collect data from almost 80 poplar trials in 11 states in the Midwest, South, and Pacific Northwest. This has provided important information on multiple topics, including disease resistance and yield estimates for many of the new higher-yielding varieties. The Partnership documented yield gains in poplar of 35% to 50% over the course of the Partnership.

4.3 Increased Access to Data for Researchers, Industry, and Policymakers

Prior to formation of the Partnership, data from yield trials were often not readily accessible to growers and business developers and were not always easy to interpret. This created a barrier to the expansion of energy crops because the uncertainties about these crops were often very high. The approach of consolidating and housing data from these trials into the Bioenergy Knowledge Discovery Framework was an important step in addressing these issues. The availability of data sets that can be accessed and used by project developers and businesses will reduce the level of uncertainty around many of the energy crops that were the focus of the Partnership. Partnership field trial data sets will be accessible soon at the Bioenergy Knowledge Discovery Framework (bioenergykdf.net).

Policymakers have made use of data from the network of Partnership trials to develop guidelines and regulations for various programs. For example, information on production and management of willow from yield trials in northern New York was used by the USDA Farm Service Agency to expand willow biomass crops in the region. With USDA conservation practices now developed and approved for use, it will be much easier to expand willow biomass crop production in other regions.

The Partnership has been very effective in acaccumulating the data that will eventually be used to drive the expansion of energy crops on the landscape. The extensive network of Partnership trials provides invaluable information for private investors that are involved in the production of energy crops. Without this information and investment, the expansion of these energy crops would be slowed or inhibited completely, because growers would have to resolve on their own many of the questions addressed by the Partnership.

For example, the Partnership collaborated with GreenWood Resources (i.e., a global timber management company specializing in the development and operation of high-yield, short-rotation hybrid poplar and cottonwood tree farms). GreenWood currently manages 30,000 acres of poplar plantations in the Pacific Northwest, including 7,000 acres of poplar biomass crops to supply regional bioenergy and biorefinery operations. The availability of elite cultivars, made possible through GreenWood Resources' involvement, has been critical to the success of the Partnership.

Information obtained through the network of willow trials, made available through the Partnership, has been widely used by nursery operators to select ideal cultivars for commercial production. Another private investor in energy crop development is Double A Willow, a commercial nursery in western New York that provides most of the planting stock for the willow biomass crop in North America. Without data from the Partnership, the transition to new, high-yielding cultivars in the nursery would have been delayed, and this material would not have become commercially available.

The importance of geographical distribution of Partnership efforts cannot be overstated, especially for development of perennial energy crops, where long-term data are needed to accurately reflect production potential and to identify potential

The sites used for the Partnership and the data generated from them provided numerous opportunities for farmers and landowners to see different energy crops and experience their management first-hand. This kind of firsthand experience with new energy crops over several growing seasons is essential to overcoming barriers and misconceptions, which needs to occur before landowners engage in the production of energy crops.

issues that may impact production over multiple years. When the Partnership formed, there were only a couple of trials of willow biomass crops in the United States that had been maintained for more than one harvest cycle, and these trials did not contain any of the new higher-yielding cultivars that were introduced in the late 1990s. Currently, the Partnership has produced data from improved cultivars over 2 harvest cycles at 12 different trials sites and over 3 harvest cycles at 4 sites. These data will greatly improve the accuracy of predicting willow biomass yields in multiple rotations.

4.4 Development of Yield Potential Maps

The Partnership supported development of yield potential maps for each species within the Partnership's research scope, which will support policy decisions and future commercial development of energy crops across the country. Average potential biomass production maps from 1981 to 2010 were produced for energycane, upland and lowland switchgrass, biomass sorghum, CRP mixed perennial grasses, miscanthus, willow, poplar, and southern pine. Mapping was done with PRISM-EM, which is a computer model that evaluates the relative reduction in biomass potential due to climate and soil limitations (Halbleib et al. 2012). Relative yield maps from PRISM-EM were scaled to represent the potential biomass yield using Partnership yield trial data (except for southern pine, which relied on published yield values exclusively). These maps provide a first look at the distribution of potential biomass production for these nationally important feedstock species. In addition to being used for economic analysis in the *2016 Billion-Ton Report*, the yield potential maps will be indispensable for organizations exploring biomass feedstock supplies in different regions of the county, addressing issues of water-use and land-use change, and determining the impact of climate change on agricultural production in the future.

The Partnership led to development of yield potential maps for each species within the Partnership's research scope, which will positively impact policy decisions and future commercial development of energy crops across the country.

4.5 The Assurance of Firsthand Experience

The sites used for these trials and the data generated from them provided numerous opportunities for farmers and landowners to study a variety of different energy crops and experience their man-

With USDA conservation practices now developed and approved for use, the expansion of willow biomass crops will be much easier to develop and implement in other regions.

agement firsthand. This firsthand experience with new energy crops over several growing seasons is essential to overcoming barriers and misperceptions, which need to occur before landowners engage in the production of energy crops.

Two of the Partnership's yield trials in the willow research group's network were located in northern New York and were used as locations for numerous outreach and education events. Students, Future Farmers of America members, landowners, farmers, state and regional policymakers, and companies followed the development of these willow trials and became familiar with their growth and harvesting operations. When the opportunity arose to develop a Biomass Crop Assistance Program project to plant up to 2,500 acres of willow in northern New York, the community, USDA, and ReEnergy Holdings were already familiar with willow biomass crops and their establishment, growth, and harvest. These newly informed groups responded to the approval of this project by committing to plant 1,200 acres of this crop. This project and successful collaboration would not have occurred without the previous experience with willow made possible through Partnership efforts. Currently, part of nearly 1,200 acres of willow in northern New York are being harvested annually and delivered to ReEnergy for the production of renewable power and heat.

CASE STUDY

The Poplar Research Group

Partnership research in poplar as a dedicated energy crop is ongoing, with 78 field research sites included in the research program. The information and genetic products produced from the Partnership poplar program are essential for advancement of both commercial ventures and demonstration projects, such as those funded by USDA's Biomass Crop Assistance Program.

The Partnership's poplar efforts have enabled continued successful commercial application of poplar plantations. For example, GreenWood Resources currently manages high-yield, short-rotation hybrid poplar and cottonwood tree farms with 30,000 acres of commercial poplar plantations in the Pacific Northwest. Partnership collaborations with the University of Minnesota, Michigan State University, Mississippi State University, and ArborGen, Inc. have been instrumental in identification of potential new commercial varieties and development of adapted breeding populations. These populations form the basis for genetic improvement programs for future projections of coppice yields.

Germplasm research through the Partnership's poplar research group resulted in significant advancements toward poplar feedstock commercialization.

Significant Outcomes:

- Clone tests demonstrated that testing of new genotypes has significant potential for increasing the growth rate and genetic diversity of poplar for commercial planting in all regions. Based on field clone tests, the yield of the fastest-growing clones ranges from 1.3 to 1.6 times that of currently available commercial clones (Berguson et al. 2012).
- Breeding has been ongoing throughout the duration of the Partnership at locations in Oregon and Minnesota, with the two programs producing more than 20,000 new clones for field testing. These programs have produced new populations of improved varieties to serve as a starting point for future clone and yield testing in the respective regions. This living collection represents the largest collection of poplar clones ever assembled (Zamora et al.).
- Genetic improvement research has produced unprecedented infrastructure of parent collections to support further breeding efforts. This network of new parental genotypes did not previously exist in the United States.
- Partnership research led to an enhanced understanding of the underlying genetic effects, with estimated yield gains of 20% per breeding cycle (Berguson et al. 2016).
- Cash flow models that were developed based on commercial poplar operations served as a basis for biomass production cost estimates as part of the *U.S. Billion-Ton Update*.
- Based on estimates of stand yields, production costs, and harvest and transport economics, DOE's delivered feedstock price target of \$80 dry ton^{-1} (2011 dollars) appears to be achievable at many sites in the Midwest (Berguson et al. 2010).
- The average annualized biomass yield of selected clones was variable across the country, ranging from 3.5 dry tons acre^{-1} in the Midwest to 8.0 dry tons acre^{-1} in the South (Berguson et al. 2012).
- New collections of promising clones produced under the Partnership have garnered global attention and led to cooperative field tests of genetic material in Europe.

5. Information Transfer

An important goal for the Partnership has been timely dissemination of information and insights generated by the research and development program, including conventional products like peer-reviewed publications and presentations at professional meetings.[5] The trial network established by the Partnership also provided the perfect backdrop for numerous field days, tours, and other landowner education programs around the country (fig. 13). Examples of other valuable outreach events and tools are described in the following subsections.

Select Partnership accomplishments through 2015:

- Published 134 peer-reviewed papers
- Published 4 book chapters
- Published 26 conference proceeding articles
- Contributed 192 presentations at meetings and conferences
- Developed 48 extension/outreach publications.

For a complete list of Partnership outputs, see online appendix B or visit the Sun Grant Initiative website.

Figure 13 | The Partnership provided many opportunities for landowners, investors, universities, and other interested parties to visit the field trial sites and see first-hand how these energy crops are cultivated and harvested. The above photo was taken during one of the field days at a poplar plantation located in Tennessee. *(Image courtesy of Jessica McCord, University of Tennessee)*

[5] A full listing of Partnership publications, reports, presentations, and other information outputs can be found in online appendix B of this report energy.gov/eere/bioenergy/downloads/regional-feedstock-partnership-report or on the Sun Grant Initiative web page at www.sungrant.org/News+and+Events/Regional+Feedstock+Partnership+Bibliography.htm.

5.1 The Sun Grant National Conference

The Sun Grant Initiative showcases regionally focused research that targets biomass, bioenergy, and bioproduct-related topics at national conferences across the United States. The 2012 Sun Grant National Conference on Science for Biomass Feedstock Production and Utilization, held October 2–5, 2012, in New Orleans, Louisiana, explored recent advances in the state of technology of supply chain operations. More than 120 presentations covering all Partnership topics were presented in parallel and poster sessions, highlighting the progress that has been made by the Partnership in resolving many of the challenges of biofuels industry expansion (table 2). A special issue published in *BioEnergy Research* (volume 7, issue 3) highlighted twelve presentations from the 2012 National Conference and corresponding products from the Partnership.[6] A special issue of *BioEnergy Research* was also developed from the national conference with a summary of the conference by McCord et al. (2014).

5.2 BioWeb

In addition to field trials and crop modeling projects, educational and outreach work is underway to help agricultural producers, industry, and other stakeholders prepare for a future that includes converting biomass crops into energy and other products. One educational product from the Partnership is the BioWeb (bioweb.sungrant.org), which is an online resource for biomass and bioenergy information. The BioWeb has drawn from some of the country's top biomass authorities to provide a comprehensive analysis of the current state of biomass production, agronomy, harvest, collection, storage and prepro-

Table 2 | Summary of General Sessions at the 2012 Sun Grant National Conference on Science for Biomass Feedstock Production and Utilization by Topic, Number of Papers, and Subject Area

Session topic	Number of papers	Subject areas
Energy crop development	14	Breeding, genetics, genomics, and yield
Biomass production	36	Inputs, soils, and nitrogen management
Biomass logistics	14	Assessment, harvest, storage, densification, and costs
Feedstock conversion	18	Processes and products
Biomass characterization	7	Composition, methods, and energy
System sustainability	14	Soil quality, residues, life-cycle analysis, and GHGs
Model and metrics	11	Siting, supply, and production
System case studies	5	Regional studies
Extension and education	4	Curriculum and dissemination
Total	**123**	

[6] Proceedings of papers from this conference can be accessed at http://sungrant.tennessee.edu/NatConference/ConferenceProceedings/.

cessing, as well as conversion technologies, and attempts to quantify impacts associated with biomass industry development, where possible. Content of the BioWeb is outlined in four major areas: (1) feedstocks, (2) biofuels, (3) biopower, and (4) bioproducts. In each of these areas, research coordinators, most from the Partnership, have assembled teams of research expertise that represents the spectrum of expertise in the biomass arena. The BioWeb was created with two distinct audiences in mind: (1) the interested public and (2) the academic specialist.

5.3 GeoSpatial Information Tools

Collaborations among regional partnerships are critical in developing sustainable biomass production and crop rotation strategies for both existing and new biomass resources. One DOE-sponsored Partnership activity was a regional and national biomass resource assessment. As part of this effort, the Southeastern Sun Grant Center worked with Oak Ridge National Laboratory to develop The Southeast Biomass Atlas (biomassatlas.org), which is a regionally focused, web-based atlas for policy and planning to support the expansion of biomass use for energy and bio-based products.

The Southeast Biomass Atlas includes a spatial, county-level inventory of dedicated energy crops, with a scope of nine states and two territories (fig. 14). The atlas includes switchgrass, sorghum, willow, and other bioenergy crops. Using all available information on the existing and proposed facilities that use biomass for energy, advanced biofuels, and pellet production, this tool provides an estimate of current and future regional biomass demand. Environmental, socioeconomic, agricultural, geographic, and industry data, coupled with data from the *U.S. Billion-Ton Update* and estimated biomass supply through 2022, provide quick access to biomass availability information in a format relevant to policymakers, industry leaders, landowners, and resource providers.

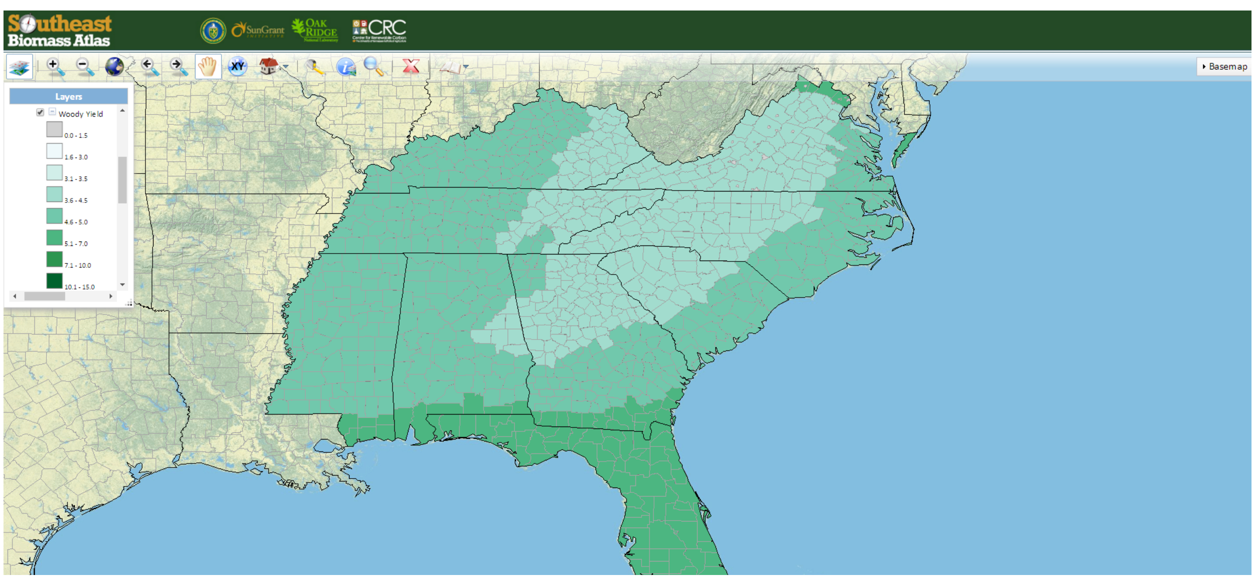

Figure 14 | Map was generated using the Southeast Biomass Atlas and depicts the availability of woody biomass in the Southeast through 2022 (information freely available at biomassatlas.org).

6. Economic Impact of Achieving the Billion-Ton Vision

Information collected through the Partnership has impacted the biomass cost of production estimates in many ways. For example, understanding average per-acre yield and the consistency of those yields, particularly for new crops, is critical to estimating the future volume of those crops. Similarly, understanding sustainable removal limits of agricultural residues and removal limits for developing crops impacts the amount of material available, which impacts economics. These were two objectives of the Partnership.

Economics-related information is critical to deployment of biomass crops for commercial use, including the costs of crop establishment, maintenance, and harvest. Landowner participation is needed for industry growth; encouraging landowner participation requires robust location-specific information about the cropping system to guide long-term cropping decisions. The Partnership's yield results have directly informed the costs of production, which, in turn, impact the ability to conduct strategic analysis of biomass feedstock options and impact the economic potential of a robust bioenergy industry.

Feedstock producers rely on accurate feedstock yield and cost projections and align business models to capture market returns. From a public perspective, policymakers may weigh production costs against the benefits of production and use this approach to determine and advance bioenergy strategies that promote public welfare (e.g., energy security and independence and climate impacts). In the case of advanced, second-generation[7] biofuels pathways, feedstock cost comprises a significant portion of biofuel production costs, amounting to up to one-third of the production cost. Therefore, strategies for reducing cost and risk to both the producer and biorefiners are critical to growing and expanding not only the biofuels industry, but also the bioenergy industry at large.

The Partnership has provided relevant yield information for seven unique biomass cropping systems at locations throughout the United States. Partnership efforts have also developed and/or identified or confirmed higher-yielding varieties of biomass sorghum, energycane, poplar, and willow. The availability of higher-yielding cultivars is an essential part of increasing bioenergy crop revenues to a level where the energy crop is cost competitive with traditional corn or other land-use options. Increasing crops yields also serves to reduce the amount of production land required to achieve the Billion-Ton Vision.

Similarly, several crop growth models using Partnership data have provided nation-wide yield

[7] Initially, biofuel development was focused on feedstocks high in sugar (such as corn or vegetable oils). This approach is commonly termed "first generation." Second-generation fuels expanded beyond those feedstocks, broadening into lignocellulosic feedstocks such as perennial grasses, woody biomass, and agricultural residues.

estimates of biomass crops, though many of them lack the ability to address all crops in a consistent framework. For example, the PRISM-EM model provides economic decision-makers with a uniform approach that allows rapid analysis of comparative biomass crop yield.

6.1 Methods in the *2016 Billion-Ton Report*

As mentioned earlier, Partnership data were used to underpin the *2016 Billion-Ton Report* and the previous *U.S. Billion-Ton Update* biomass resource assessments, particularly for sustainable removal yields and energy crop yield projections. The Partnership's field-level validation of the quantity of biomass that can be sustainably removed from the field impacted the grower payment (which is derived from the farmgate price) that is estimated through resource assessments. The data from these assessments is used to further define delivered feedstock cost, which is a critical component of total bioenergy production cost, and is composed of feedstock logistics cost (i.e., harvest and collection, preprocessing, transport, and storage) plus a grower payment. Therefore, Partnership trials have played an important role in determining the potential amount of biomass that could be available at a defined delivered cost in a given year.

The Partnership has made other important contributions in crop residue and energy crop management strategies. Crop residues provide important environmental benefits, such as protection from wind and water erosion, maintenance of SOC, and soil nutrient recycling. Thus, not all produced crop residues are sustainably available. Sustainably available residue removals are constrained to not exceed the tolerable soil loss limit of the USDA Natural Resource Conservation Service (NRCS), and to not allow long-term reduction of SOC as estimated by the Revised Universal Soil Loss Equation (RUSLE and RUSLE2) (Renard et al. 1991; Weesies et al. 2001) and the Wind Erosion Prediction System (Bilbro 1991).

To address soil loss within perennial crops, a new model was developed within RUSLE2 that enables the use of this model with perennial crops (Dabney and Yoder 2012). Using these models, county-level average sustainable biomass removal levels are calculated for wind, rain, and soil carbon for each rotation and tillage strategy by NRCS-defined crop management zone. Partnership data were critical in the development and validation of this national supply assessment approach for residue and perennial crop management, which provides the underpinning for county-level resource assessment (Muth and Bryden 2012).

Yield information collected through the Partnership has contributed to estimating potentially available feedstocks, and some yield information fed into the Policy Analysis System (POLYSYS) model (Torre Ugarte and Ray 2000). POLYSYS was used in the *2016 Billion-Ton Report* to estimate potential available supplies of agricultural resources. The POLYSYS model was previously developed to simulate changes in economic policy, agricultural management, and natural resource conditions and to estimate the impacts to the U.S. agricultural sector from these changes. POLYSYS is used to estimate how agricultural producers may respond to new agricultural market opportunities (such as a new demand for biomass), while simultaneously considering the impact on other non-energy crops.

POLYSYS simulates (a) crop supply for the continental United States, (b) national crop demands and prices, (c) national livestock supply and demand, and (d) agricultural income. Variables that drive the modules include planted and harvested area, production inputs, yields (see table 1), exports, costs of production, demand by use, commodity price, government program outlays, and net realized income. The per-acre yields of agricultural residues are based on USDA data, and the sustainable removal limits were developed using Partnership-generated data.

Second-generation biofuel crops, including dedicated energy crops, are also considered in POLYSYS. Those yield projections are based on Partnership data in coordination with the Oregon State University PRISM modeling group. Contributions from dedicated energy crops (such as switchgrass and poplar) are not included in the early years of the simulations to allow time for the scale-up and establishment of these crops. Inputs from dedicated energy crops are included in the national resource assessment beginning in 2019.

It should be noted that *2016 Billion-Ton Report* data do not account for yield enhancements due to nitrogen fertilizer addition for energy crop projections; therefore, yield projections for some energy crops can be considered very conservative. As an example of how significant this new information could be, yield improvements as high as 88% have been recorded with the addition of moderate amounts of nitrogen fertilizer to certain switchgrass plots (Hong et al. 2014). Scenarios for yield improvements over time may be achieved with a mix of improved management practices and crop breeding efforts, collectively modeled as base-case and high-yield scenarios. In the 2011 *U.S. Billion-Ton Update*, the base-case scenario assumed 1% yield improvements per year, with high-yield scenarios achieving 2%, 3%, and 4% yield improvements per year (DOE 2011). These scenarios were developed in the high-yield workshops that occurred during the development of the Partnership (DOE 2010). These scenarios were also used in the *2016 Billion-Ton Report*.

6.2 Future Perspectives

Early commercial planting of bioenergy crops across the United States has provided validation of early stage biomass production costs. However, the bioenergy crop industry still remains regional and extremely sparse. Enabling the full potential of national agriculture and forestry sectors to provide high-quality biomass requires further investment in crop development and machinery advancements necessary for efficient scale-up of the technology. Short and long-term rollout of the economic analysis involves refinement of costs, which includes these incremental advancements in crops and machinery that provide necessary economies-of-scale for commercial deployment. A necessary next-step involves the refinement of costs that incorporate advanced feedstocks into cost calculation equations and reanalysis of point yield estimates and distributed supply yields at the farm and regional level.

7. Impact of Feedstock Quality on Conversion and Yields

Biomass quality is important because quality characteristics impact downstream conversion operations. Variations in quality can affect the yields of biomass conversion processes, and therefore the profitability of the biorefinery. Valuation of biomass strictly on a weight basis (i.e., $ dry ton-1) with limited focus on biomass quality could result in poorly performing conversion processes due to high variability in the feedstock composition and low quality biomass. The multi-location Partnership effort, combined with the long-term nature of the Partnership trials, created a truly unique opportunity to begin assessing the natural variability of feedstock quality attributes found in biomass feedstocks and how this variability could affect biomass conversion processes.

The impact of location, year, environment, harvesting operations, storage conditions, and other agronomic treatments on feedstock quality is explicitly important for understanding feedstock variability at the local and national levels; this ultimately impacts the practicality of using a specific feedstock resource for a particular conversion process.

Feedstock samples collected through the Partnership have begun to fill the void of information related to biomass feedstock quality. The Partnership has collected thousands of biomass samples from several crop species and geographic locations across the nation, from many different environments and soil types, and over a number of years with varying weather conditions. The collection and analysis of such an extensive number of samples, correlated with additional data collected (such as growth conditions, weather patterns, and biomass yields) have provided critical information that can be used to accurately estimate national biofuel production potentials.

7.1 Sample Analysis

Sample analysis from Partnership field trials has greatly increased understanding of the sources and impacts of feedstock variability because there is no other comparable data set of this scale and long-term nature. Biomass evaluated for quality through the Partnership includes switchgrass, miscanthus, CRP mixed perennial grasses, energycane, and biomass sorghum. Samples from willow and polar clones have also been made available. The analyzed biomass was collected from 2008 until 2014 as part of Partnership field research efforts. Chemical composition, including carbohydrates, lignin, ash, and volatiles, was determined for almost 2,000 samples using spectroscopy methods developed at the National Renewable Energy Laboratory (Wolfrum and Sluiter 2009) and Idaho National Laboratory. As seen in figure 15, quality can be highly variable, and this variability can affect performance and product yield in conversion systems, which, in turn, affects process economics.

There are two primary types of systems for converting biomass to energy, fuels, or chemicals: (1) biochemical and (2) thermochemical. Generally, biochemical conversion technologies involve pathways that use sugars and lignin intermediates, while thermochemical conversion technologies involve pathways that use bio-oil and gaseous intermediates (DOE 2016b). Note that these definitions do not fully encompass the diversity of conversion technologies, particularly, emerging ones.

7.1.1 Biochemical Conversion

The high carbohydrate content in biomass is desirable for biochemical conversion of biomass to fuels, because it is the carbohydrates that are converted to products. The amounts of carbohydrates (i.e., mainly glucan and xylan) present in herbaceous grasses and hardwood tree species biomass vary considerably for all biomass types collected by the Partnership, ranging from about 30% to 65% (fig. 15).

Miscanthus had the highest average carbohydrate content, followed by switchgrass; this makes them well suited for biochemical conversion processes. However, lignin concentrations are also high for both miscanthus and switchgrass (fig. 15). High lignin concentrations can have a negative impact on some of the biochemical processes that produce ethanol. CRP mixed perennial grasses and biomass sorghum have the lowest carbohydrate content of all feedstocks analyzed, but also have the lowest lignin contents.

The Partnership has begun to define the variability of carbohydrate and lignin content found in biomass feedstocks. A detailed understanding of this variability is critical to selecting a feedstock that will perform well in a biochemical conversion system.

Note that in figure 15, the data values are expressed on a dry weight basis and include extractives. Extractives can be considerable in whole biomass samples of sorghum and energycane and can therefore significantly reduce the amount of other chemical constituents of the biomass. Energycane samples were received as bagasse that had been pressed prior to analysis, so most of the water-soluble extractives (i.e., sucrose, etc.) have been removed from the sample prior to analysis. Sorghum samples were received either as whole biomass or as bagasse that had been pressed prior to analysis.

In any biomass conversion processes, ash cannot be converted to fuel. High ash content leads to lower yields of fuels and chemicals per ton of biomass fed into the conversion process. Ash can also interfere with some chemical reactions that are necessary for efficient biochemical conversion to take place, again reducing yields (Weiss et al. 2010). Of the herbaceous grasses tested, miscanthus samples had some of the lowest ash values, followed by switchgrass and energycane (fig. 15), indicating that these feedstocks may be more desirable for conversion processes. CRP mixed perennial grasses and sorghum samples had the greatest ash contents and may be more suitable for blending with higher quality feedstocks such as miscanthus and switchgrass in order to be a suitable biochemical conversion feedstock.

Weather patterns can also influence biomass quality. The Partnership crop trials were in process during the widespread drought in 2012. Miscanthus and CRP mixed perennial grasses collected during 2012 were used to determine the impacts of drought on feedstock quality. During this drought year, there was an overall reduction in biomass yield, plus the harvested biomass was

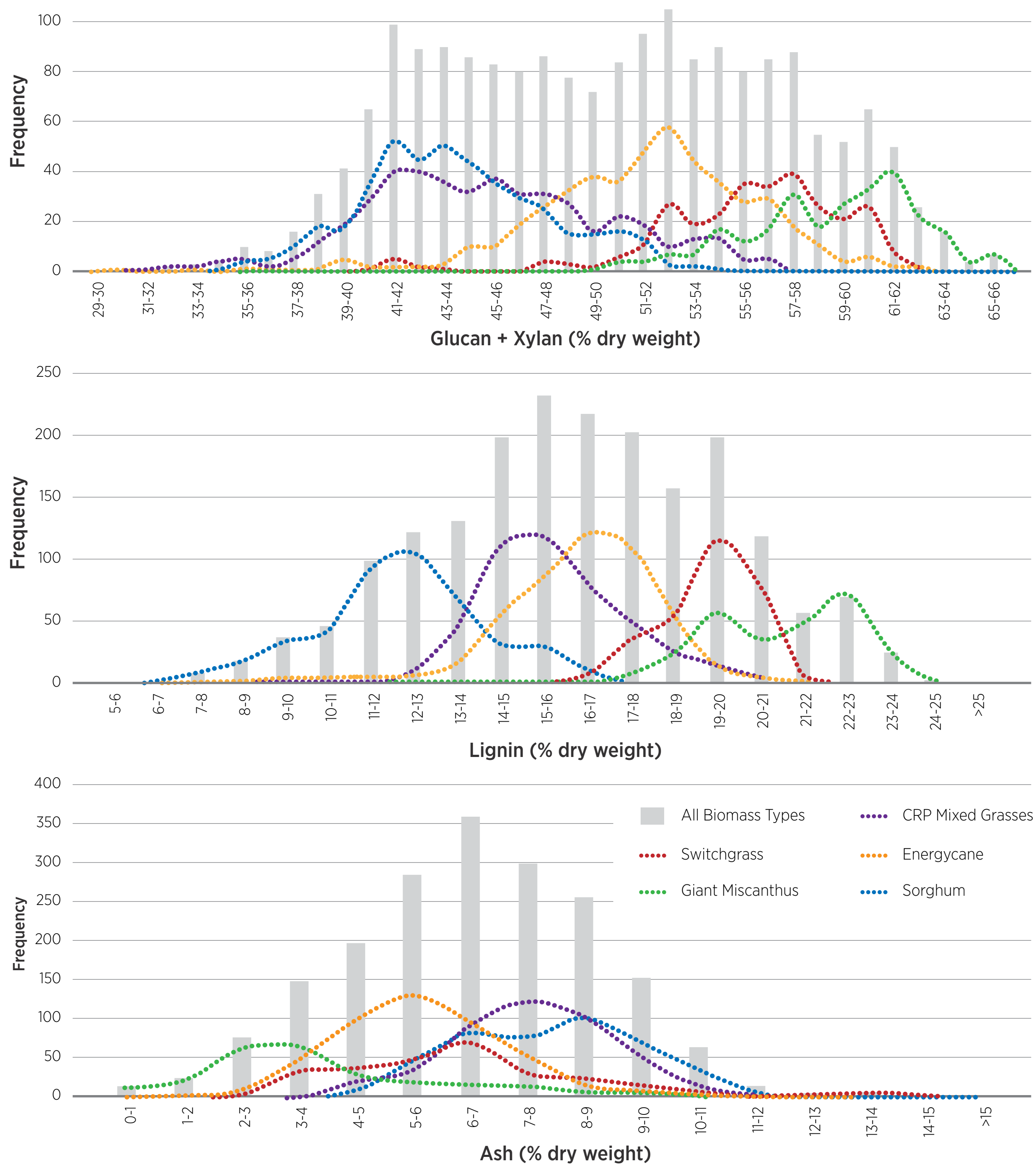

Figure 15 | Histograms showing percent structural carbohydrates (% glucan plus % xylan) (*top*), percent lignin (*middle*), and percent ash (*bottom*), from four biomass types collected through the Partnership. Sample and analytical replicates were averaged and expressed on a dry weight basis. Frequency is the number of samples that fit each percentage (%) bin. Weather variability, in addition to feedstock type, was found to have the most significant impact on the quality of the Partnership feedstocks.

lower in carbohydrate content (Emerson et al. 2014). Together, the low yield and low carbohydrate content during a drought year could significantly decrease the amount of fuels and chemicals that could be produced.

7.1.2 Thermochemical Conversion

In thermochemical conversion processes, ash is also unconvertible material, but can also negatively impact the conversion yields and can be harmful to the equipment (Tumuluru et al. 2012). Thermochemical conversion processes have historically used woody feedstock materials due to their very low ash content; however, low ash feedstocks such as miscanthus could be added to the woody feedstocks during the conversion processes. Biomass quality data obtained through the Partnership can be used to identify additional low-ash feedstocks that may be suitable for inclusion in thermochemical conversion processes as a blendstock.

While many of the miscanthus samples collected by the Partnership would be suitable for inclusion with woody feedstocks in thermochemical conversion processes, some of the individual miscanthus samples still did have elevated ash content (fig. 15) for reasons that are not yet clear; these feedstocks may not be good candidates for inclusion in thermochemical conversions. Variations in quality need to be addressed prior to using biomass feedstocks in conversion processes.

Increases in lignin content have been shown to improve yields in thermochemical conversion processes (Jenkins et al. 1998; Demirbas 2004). Because woody samples generally have high lignin content (Williams et al. 2015), specific herbaceous feedstocks would need to be carefully selected (i.e., for maximum lignin content) if they were going to be mixed in large proportions with traditional woody feedstocks for use in thermochemical feedstock blends. Of the samples collected through the Partnership, miscanthus tended to have the highest lignin content.

7.1.3 Summary

The comprehensive data set from the Partnership, in combination with characterization results from commercial-scale harvesting, is useful for determining the natural variability in feedstock quality and establishing initial grades for investigated feedstocks, as well as feedstock and conversion process selection decisions. Examples of general conclusions that can be drawn from feedstock quality data collected by the Partnership include the following:

- Miscanthus had greater carbohydrate content and lower ash content. Miscanthus also had a higher volatile content.
- Switchgrass had greater structural carbohydrate content than CRP mixed perennial grasses, sorghum, and energycane, but also higher lignin content.
- CRP mixed perennial grasses and sorghum had the lowest structural carbohydrate and lignin contents and the highest ash content.
- Drought decreases carbohydrate content and biomass yield, indicating a risk to the feedstock supply chain during drought years.

- Miscanthus and switchgrass may perform well in a biochemical conversion process if the higher lignin content of these feedstocks does not decrease conversion performance.
- Miscanthus might also be a stronger performer in thermochemical conversion processes due to its low ash content and higher lignin and volatile contents.

As additional samples from across the country are analyzed and added to the quality information database, and as these quality attributes begin to be correlated to conversion performance, a grading system that is specific to the different conversion processes can be established and feedstocks with specific quality attributes can begin to be matched with the selected conversion processes to optimize performance and yields of fuels and chemicals.

8. Partnership Impact and Path Forward

The Regional Feedstock Partnership has helped quantify future biomass potential, which is critical to understanding the U.S. bioeconomy's potential. Model-based estimates are an important part of this effort; however, observed biomass yields are necessary to confirm biomass resource assessments, particularly for the new and emerging bioenergy industry. For example, through careful site selection and species management, the Partnership provided the necessary validation for the DOE-funded Billion-Ton resource assessments.

Field-level validation of resource assessments is not only important for developing and gauging progress toward bioenergy production goals, but these validations also support development of energy crops through improved policy making, management, and risk-aversion strategies. Throughout the lifetime of the Partnership, new varieties of energy crops have become available, and some cultivars of willow and poplar have attained yield increases of 15% to 50% above existing commercial varieties.

The Partnership generated an unprecedented volume of information, particularly related to yield, on existing and emerging crops for bioenergy production. The longevity of the project enabled data collection under diverse weather conditions, including a major drought, the study of a variety of site and genetic combinations, and sustainable management practices. This progress was coupled with subsequent advances in scientific and technical knowledge to support large-scale energy crop deployment.

As was highlighted in section 4, many stakeholders have benefitted from information that was generated through the Partnership, including, but not limited to, crop growers and landowners (such as Double A Willow and ArborGen), researchers in academia and industry, national laboratories, and decision makers in the federal government. Agriculture and natural resource professionals working for local, state, and federal government have used Partnership data to develop best management and conservation practices that have become part of the guidelines and regulations for government agriculture programs. For example, information on production and management of willow from yield trials in northern New York was used by the USDA Farm Service Agency to expand willow biomass crops in the region.

With USDA conservation practices now developed and approved for use, it will be much easier to expand willow biomass crop production in other regions. Companies, such as ReEnergy Holdings and GreenWood Resources, have used this information to create new jobs in rural areas by developing new business opportunities and new supply chains for biomass feedstocks, biofuels, and bioproducts. Policymakers, such as at the USDA Farm Service Agency, are using information from the Partnership to project future sustainable production of biomass across the country and to develop guidelines and policies related to development of bioenergy, biofuels, and bioproducts industries.

Maintaining a network of biomass plots over many consecutive years has also provided comparative test materials under standardized protocols for compositional studies and other analytical research needs. Larger field plots have provided supplementary cost and logistics data and resources for sustainability studies (e.g., soil and water quality, GHG emissions, biodiversity, and integrated landscapes), and have been used for a variety of demonstrations and outreach activities. In the coming years, provided additional funding were to become available, existing and new Partnership Field Trials could be used to more completely assess regional biomass potential by capturing energy crop yield data and analyses over even wider geographical, temporal, and environmental ranges than currently available.

USDA-ARS, the National Institute of Food and Agriculture, and the U.S. Forest Service have been actively involved in the Partnership and in DOE BETO's Terrestrial Feedstock Supply and Logistics R&D Program for decades. Continued collaboration between the agencies is critical for the development of useful and practical science that is needed to help manage risk and resolve uncertainty in business models for energy crops, as well as to support DOE's continuous and dedicated program that provides a national biomass resource assessment. This effort has been recognized as "world-class" and is used by many as the sole source of information on biomass availability. The *U.S. Billion-Ton Update*, which is largely underpinned by Partnership data, has been referenced in hundreds of peer-reviewed publications.[8] The Partnership represents an excellent model of collaboration among several dozen land grant universities, government agencies (e.g., DOE and USDA), and industry researchers, resulting in significant accomplishments. Having a formal partnership among these organizations improves collaboration, information exchange, and coordination of research and data processing efforts. The result is accelerated outcomes, innovative science, and increased efficiency.

[8] "Web of Science" query, May 2016 (www.webofknowledge.com).

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A full listing of all Regional Feedstock Partnership publications, presentations, reports, and other information outputs can be found in appendix B at energy.gov/eere/bioenergy/downloads/regional-feedstock-partnership-report or at the Sun Grant website: www.sungrant.org/News+and+Events/Regional+Feedstock+Partnership+Bibliography.htm.

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