This is a supplemental appendix to the *Regional Feedstock Partnership Summary Report*, prepared for the U.S. Department of Energy's Bioenergy Technologies Office, July 2016, by the Sun Grant Initiative and Idaho National Laboratory.

Appendix A: Crop/Team Reports

Contents

Figures

Tables

1. Corn Stover

1.1 Description/Characteristics

Corn stover, the aboveground plant material left after grain harvest, was identified as a major potential cellulosic feedstock for bioenergy production because of the vast area used for corn production in the United States (Karlen et al. 2014). It was selected as a focal point for one of the Regional Feedstock Partnership (the Partnership) teams based on *Billion-Ton Study* (*BTS*) projections that stover could supply 75 million of the 446 million dry tons of crop residues available for U.S. bioenergy production (Perlack et al. 2005). The U.S. Environmental Protection Agency (EPA) concurred that stover was, indeed, "the most economical agricultural feedstock…to meet the 16 billion gallon cellulosic biofuel requirement" (Schroeder 2011). Furthermore, based on energy use, energy security, and several resource conservation metrics, Lavigne and Powers (2007) concluded that using corn stover as a feedstock for advanced biofuel production was more consistent with U.S. national energy policy priorities than producing them from grain.

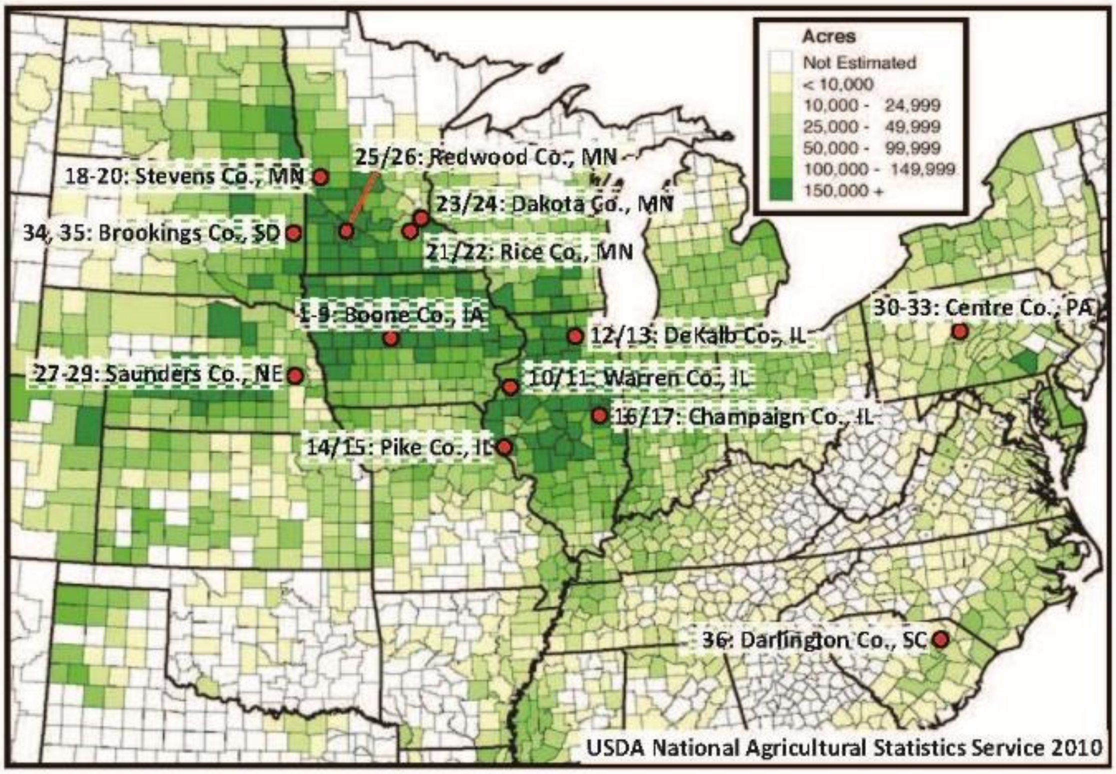
It was envisioned that the agricultural community would rapidly embrace corn stover harvest since farmers have been collecting it for many years for use as animal feed and bedding and since a substantial amount of research had been conducted on its use as a bioenergy feedstock following the 1970s oil crisis. From a producer's perspective, harvesting corn stover could also help reduce residue management costs, which currently range from \$20 to \$30 per acre (acre^{-1}) (Plastina 2015) and are expected to rise as grain yields increase. However, before assuming that corn stover is abundantly available and simply waiting to be harvested, it is important to recognize that it already provides many important ecosystem services that include (1) protecting surface soil from raindrop impact and wind erosion, (2) reducing runoff and soil erosion, (3) providing a renewable source of carbon for maintaining soil organic matter (SOM), (4) recycling essential plant nutrients, and (5) reducing evaporative loss of soil water (Baumhardt et al. 2013) that can be crucial for subsequent crop production as annual weather patterns become more variable. Furthermore, it is also important to recognize that stover harvest will increase annual nutrient removal (Karlen et al. 2011, 2012) when compared to harvesting only the grain.

1.2 Objectives

The Partnership's Corn Stover Team was formed in 2008 by the U.S. Department of Agriculture's (USDA's) Agricultural Research Service (ARS) scientists, university extension and research faculty affiliated with the North Central Sun Grant Association, and engineers from the U.S. Department of Energy's (DOE's) Idaho National Laboratory. The overall goal was to quantify the amount of corn stover produced at several locations and the effects of moderate and high stover-harvest rates on subsequent crop yields, as well as other potential indicators of sustainable biomass harvest.

1.3 Methods

A core experiment consisting of no-tillage (or the least amount of tillage necessary to establish a corn crop), three rates of stover harvest (none, moderate, and high), and four replicates was agreed upon for each Partnership site. In addition to new experiments, several established long-term ARS and university field trials, designed to assess crop residue-harvest effects, were leveraged to build a more robust dataset. New and existing studies across the Corn Belt and eastern United States (fig. 1-1) provided 239 site-years of data from 36 field experiments using replicated plots that ranged in size from 0.1 to 5.0 acres. With regard to genetic resources, all sites used commercial corn hybrids recommended for the location based on grain yield, and the same hybrids were not necessarily grown at each site. As a well-established crop, corn has substantial genetic diversity, so when cellulosic conversion facilities are operating commercially, it will be very easy to increase vegetative biomass yields by transitioning to other hybrids, such as those currently grown for corn silage production.



USDA National Agricultural Statistics Service 2010

Figure 1-1 | Map showing Sun Grant Regional Feedstock Partnership corn stover sites.

With regard to the type of land upon which the studies were run, 31 were within the traditional U.S. Corn/Soybean Belt. Four Pennsylvania sites were selected because of increasing corn and soybean production in that area and because of ongoing complementary research focused on quantifying greenhouse gas (GHG) loss from those production systems. Those 35 studies were conducted on loam, silt loam, clay loam, or silty clay loam soils. A 36th site, located on loamy sand in the southeastern Coastal Plain near Florence, South Carolina, was included because a similar multi-location stover harvest study had been initiated in that location (Karlen et al. 1984) following the 1970s energy crisis. Furthermore, it was hypothesized that if adverse effects of stover harvest were going to be detected quickly, it would more likely be on highly weathered loamy sand than on well-structured, heavy-textured soils in the Midwest. In addition to the desired "no-tillage" treatment, moldboard or chisel plowing, disking, or strip tillage treatments were evaluated at various sites. The length of time for which stover was harvested and reported on as part of the Partnership study ranged from 5 to 12 years (Karlen et al. 2014).

1.4 Results/Outcomes

Collectively, the 36 research sites, located in seven states from South Dakota to South Carolina, provided 239 site-years of data with corn grain yields ranging from 80 to 227 bushels per acre (bu acre^{-1}). When averaged across all sites, years, management practices, and hybrids, grain yields for the no-, moderate-, and high-stover harvest rates, which averaged 0, 1.7, and 3.2 tons per acre (tons acre^{-1}), respectively, were 156, 160, and 160 bu acre^{-1} (Karlen et al. 2014). Compared to National Agricultural Statistics Service (NASS) records, average corn grain yield from no-stover removal treatments averaged 6 bu acre^{-1} less than the 5-year average for the counties in which the studies were conducted (NASS 2014). Moderate- and high-stover removal treatment yields averaged 1.6 bu acre^{-1} less than NASS values. Comparisons between the no-removal and moderate- or high-removal treatments showed an increase of 5 bu acre^{-1}, indicating that stover harvest resulted in a slight increase in average grain yield. No-removal treatment yields were lower due to residue management problems such as nitrogen immobilization and slower early-season plant growth and development.

The study also showed that compared to harvesting only corn grain, stover harvest increased nitrogen, phosphorous, and potassium removal by at least 16, 2, and 18 pounds per ton (lb ton^{-1}) of harvested residue. This increased nutrient removal may or may not affect fertilizer requirements depending on the current soil fertility status and long-term management history, but it does emphasize the importance of using routine soil testing and monitoring of plant nutrient status to ensure crop productivity is not being impaired by the more intensive land use associated with both grain and stover harvest.

The multi-location research also documented that stover harvest decisions must be site- or even subfield-specific (Bonner et al. 2014a, b) to minimize crop residue-management problems when yields are high, while ensuring that adequate surface cover and carbon inputs are left in the field to protect soil resources against wind- or water-induced erosion and to sustain or increase SOM. Modeling of sub-field management strategies using data from the Partnership corn stover studies showed that use of no-tillage, cover crops, and vegetative conservation barriers could increase available feedstock production in Nebraska, Iowa, Illinois, Indiana, and Minnesota by 134 to 176 million tons per year (tons yr^{-1}). This was a substantial increase from the original *BTS* projections.

The study also provided data verifying the breakeven field-edge biomass price for two of the partnership sites. Several site-specific factors influenced the prices (Archer et al. 2014), which ranged from $23 to $38 ton^{-1} in Iowa and from $49 to $66 ton^{-1} in North Dakota. The breakeven field-edge price does not include any costs associated with production, as these are assigned to the grain. This price also does not include any profit for the producer.

With regard to soil health, the study showed that when average grain yields were below 175 bu acre^{-1}, continuous stover harvest for 10 years, even with no-tillage practices, reduced particulate organic matter (POM) carbon accumulation (Karlen and Johnson 2014). POM is one of the active carbon components of total SOM and is therefore more responsive to soil and crop management changes than the entire SOM pool. Harvesting stover from areas with low-average corn grain yields also shifted dry aggregate distributions toward smaller soil aggregates, which are more vulnerable to the erosive forces of wind and water. An average minimum rate of crop residue return was calculated using 35 of the 239 site-years of data, although the extreme variability associated with different soils, weather patterns, and crop growth conditions did result in a high standard deviation (2.84 ± 0.98 tons acre^{-1}).

Regional soil GHG emissions, another critical sustainability issue, were quantified by Jin et al. (2014) for residue and tillage management effects for nine corn-production systems across the U.S. Corn Belt. Using static chamber techniques, they found that stover harvest decreased soil carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions by 4% and 7%, respectively, compared to no-stover removal. In contrast, automated continuous GHG measurements by Baker et al. (2014) showed no effect of full or partial stover removal on site-specific soil N_2O emissions. Full stover removal, however, did decrease CO_2 emissions compared to no removal. Ultimately, changes in soil organic carbon (SOC) stocks, not soil CO_2 emissions, will determine whether a production system will be a net GHG source or sink. Because management effects on SOC changes can be offset by increased emissions of N_2O, coupling soil GHG measurements with long-term SOC changes across multiple ARS sites will determine the potential for different management practices to mitigate or exacerbate the global warming potential of corn stover removal systems. An overall assessment of the information obtained through DOE's investment in the Corn Stover Team is that through this multi-location, multi-agency effort, variability in corn stover yield and availability due to soil resources, weather patterns, and management practices are now documented with much greater accuracy. Adapted, commercial hybrids were used at each site, and therefore, grain yields were consistent with NASS data, but the studies also documented the importance of site- and/or subfield-specific management for optimum grain and feedstock production.

With regard to sustainability, DOE investment in the Corn Stover Team provided information on stover yield, subsequent grain yield impacts, and nutrient removal (Karlen et al. 2014). This information can impact not only producer costs but also decisions regarding the biochemical and/or thermochemical processes used to convert the feedstock to ethanol or an advanced biofuel (Cantrell et al. 2014). This investment has also resulted in valuable insights regarding SOM (Johnson et al. 2014), soil aggregation effects (Osborne et al. 2014), and the GHG impacts (Jin et al. 2013) of various stover harvest strategies. Precipitation and temperature patterns in the southeastern United States were found to be highly correlated with corn stover composition (Cantrell et al. 2014), indicating that, in addition to their effect on biomass yield, weather patterns can also affect conversion, quality, and performance of potential biofuel production operations. Furthermore, Cantrell et al. (2014) used data from the Florence, South Carolina, site to quantify gross energy distribution associated with various fractions of the corn plants. Based on 4 years of research, they concluded that harvesting 25% to 100% of the aboveground biomass could supply between 11.4 and 64.4 MMBtu (million Btu) per acre (MMBtu acre^{-1}) (100 to 565 gallons or 378 to 2,136 L of gasoline acre^{-1}), depending upon annual rainfall. Alternatively, at the highest yield-level measured at their location (11.4 Mg ha^{-1} or 181 bu ac^{-1}), this feedstock could support a 500-megawatt (MW) power plant with a stover collection radius of 20 miles.

The primary barriers to developing successful corn stover-based bioenergy feedstock-production facilities are (1) spatial and temporal variability in crop growth and stover production; (2) multiple ecosystem service demands for which corn stover is already needed; and (3) harvest, storage, and transport challenges. All three were addressed by using Partnership funds to enhance research being conducted by Corn Stover Team members. This synergistic relationship contributed important information that has helped advance the cellulosic-based biofuel industry, thus demonstrating the importance of the DOE investment in the Partnership. An example of collaboration between ARS and DOE scientists and engineers is transferring research data from the ARS-REAP databases into the Bioenergy Knowledge Discovery Framework (KDF). This data-sharing capability also provides a conduit for the Bioenergy KDF to query the ARS Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) database, which contains important GHG data for multiple U.S. locations (Del Grosso et al. 2014) (http://nrrc.ars.usda.gov/arsdataportal/#/Home).

One of the most significant outcomes of the Corn Stover Team was the synergy that the Partnership provided for coordinated interagency and multi-location research that was conducted to address a common goal—determining sustainable corn stover feedstock-production strategies. Two examples of how the Partnership led to new and creative outcomes are illustrated first by the studies Lehman et al. (2014) conducted while by examining crop residue harvest impacts on the soil microbial community. Using fatty acid and DNA analyses of soils from four locations (Brookings, South Dakota; Florence, South Carolina; Ithaca, Nebraska; and Morris, Minnesota) with contrasting soil, climatic conditions, and differences in SOM and pH, they showed that high (~3.2 tons acre^{-1} yr^{-1}) stover harvest rates tended to reduce the fungal to bacterial ratio. This response was correlated with decreased aggregate stability and an increase in the erodible fraction as discussed by Osborne et al. (2014). The second major development was that the LEAF (Landscape Environmental Assessment Framework) model used by Bonner et al. (2014a) to examine tillage, cover crop, and conservation barrier effects now provides a foundation for a small company (AgSolver, Inc.), which is having success in changing the approach that innovative farmers are actively considering for improving management decisions and therefore profitability and environmental stewardship on their land.

The 5-year Partnership investment in the Corn Stover Team's research leveraged information from other ARS Renewable Energy Assessment Project (REAP) sites, which also contributed to DOE's Bioenergy KDF platform. Furthermore, as a result of industry, ARS, university, and DOE interactions, ARS-REAP, at the request of the Partnership's industry partners, was rebranded as the Resilient Economic Agricultural Practices team in 2012. The goal of this rebranding was to retain the REAP acronym, which emphasized the broader soil health and sustainability aspects of the studies, in addition to providing long-term, sustainability data regarding effects of repeated stover harvest.

Based on the outcomes, innovative research approaches, and technology transfer that originated as a result of the Corn Stover Team partnership, our recommendation is to focus future efforts on developing landscape-based management strategies that capitalize on sub-field variability to transition producers from continuous corn or simple corn-soybean rotation to more diverse landscape-management plans. These plans would incorporate perennials into portions of each field that are non-profitable for row-crops and are also environmentally sensitive to soil loss (erosion), nutrient leaching, or runoff. Such changes are projected to not only increase available biomass feedstock supplies (Bonner et al. 2014b), but also decrease soil erosion and nutrient losses that are currently impairing water and air quality because of the "leaky" nature of current agricultural practices. Harvest, storage, and transport (HST) calculations using Corn Stover Team results are also strengthening arguments that to facilitate feedstock transport and handling within biorefineries, greater attention should be given to the development of localized processing depots. For example, this includes depots where stover and other feedstock materials can be blended and compressed into pellets that have specific characteristics allowing them to be subsequently stored and transported more efficiently.

1.5 Key Outputs

As of July 2014, at least 36 peer-reviewed manuscripts, 8 outreach publications, 20 proceedings papers, and 39 presentations were delivered. The Corn Stover Team funds also helped support 8 graduate students and another 10 undergraduate students.

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2. Switchgrass

2.1 Description/Characteristics

Among the many grasses and crops explored for biomass-to-bioenergy systems, switchgrass (*Panicum virgatum* L.) has garnered perhaps the greatest attention (Parrish and Fike 2005). As a potential biofuel feedstock, the species has high productivity and broad adaptability, is suited to marginal sites, and is native to North America. These all have been important factors in the choice of switchgrass as a model energy crop (Kszos et al. 2000), and they were central to its use in these studies.

Switchgrass has broad genetic diversity, which, in turn, facilitates its expansive native range extending from Canada to Mexico and from the Atlantic Coast to the Sierra Nevada Mountains. In addition, the plant is divided into upland and lowland ecotypes of northern and southern origin. The ecotypic description reflects the typical adaptation of plant materials on the landscape in the mid-latitudes of the United States (roughly 37°–40° North).

Lowland ecotypes are larger, more robust plants, reaching greater than 3-m heights under ideal conditions. In contrast, upland ecotypes generally are finer-stemmed and shorter, with thicker roots and longer root internodes. These root morphological traits leave upland ecotypes appearing more as a sod-forming grass, while lowlands have a bunchgrass appearance.

2.2 Objectives

Given the wide variation in cultivars, sites, and site suitability, the intent of the switchgrass feedstock Partnership trials was to conduct production research across diverse sites using best management practices at field scale (~1 acre or larger) with standard farm equipment. A component of this objective included testing the production response of switchgrass to various nitrogen-application rates across these diverse sites. In addition, soils at the sites were sampled prior to the start of the study to determine changes in soil carbon over time as a response to switchgrass production and nitrogen treatment.

2.3 Methods

Because of its broad adaptability, a wide range of sites were chosen for this study (fig. 2-1). Conditions at the various sites encompassed much of the soil and climatic diversity encountered in the growing range for switchgrass. In addition to being relevant for various bioenergy schemes, the wide range in conditions provided additional information for the geospatial modeling team. Field trials were planted initially at five sites (Alabama, New York, Oklahoma, South Dakota, and Virginia) in 2008, with the initial fertility applications and cropping year occurring in 2009. A site in Iowa was added to the project in 2009 (with production starting in 2010). The Alabama trial failed to establish in 2008 and 2009, and was replanted in 2010 with treatments initially applied in 2011. The final crop year for this research occurred in 2015, with final soil samples collected in spring 2016.

Trials were implemented using commercially available equipment for all field operations (site preparation, planting, fertilization, and harvest). Plot sizes were about 1 acre or larger.

Three nitrogen rates (0, 50, and 100 pounds of nitrogen per acre [lb N acre^{-1}]) were applied in this study. Nitrogen sources varied by site and were limited to urea or ammonium sulfate. Treatments were replicated four times within each site.

The switchgrass cultivars planted varied by site and were selected based on our understanding of productivity, site adaptation, and seed availability. Upland ecotypes used at more northern locations included “Cave-in-Rock” (Iowa and New York) and “Sunburst” (South Dakota). Although the Oklahoma site is warm enough to support a lowland ecotype, seeds were not readily procurable because of high demand due to other large-scale plantings occurring at that time. Thus, "Blackwell," a regionally derived and adapted upland cultivar, was planted in Oklahoma. "Alamo," a broadly planted lowland ecotype that had been used in previous local and regional trials (Bransby and Huang 2014; Fike et al. 2005, 2006; Ma et al. 2001) was planted both in Alabama and in Virginia.

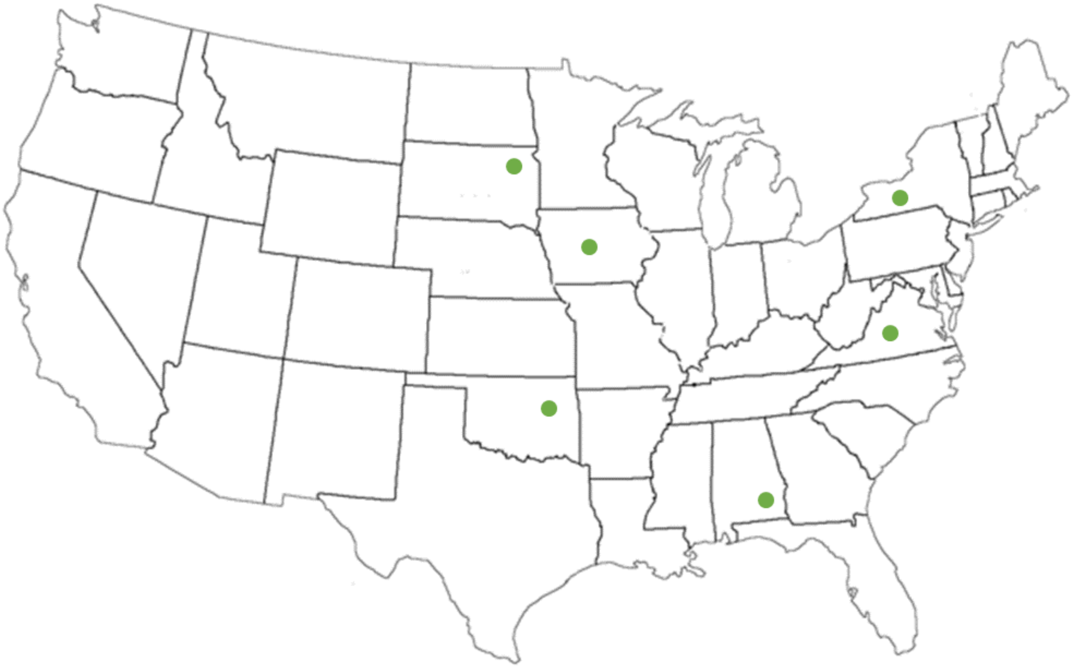

Figure 2-1 | Map showing Sun Grant Regional Feedstock Partnership switchgrass evaluation sites.

Lands used for these sites were generally considered marginal relative to other sites in the region. Previous crop use at these sites largely had been soybeans or forages. Research in Alabama, Iowa, New York, and Oklahoma was conducted on university farms, while the work in South Dakota and Virginia was conducted by farmers on commercial operations.

2.4 Results/Outcomes

Large yield variation was observed among sites over the course of the study—not unexpected given the range of sites, site conditions, and cultivars used for this research. Yields in the first production year (i.e., the year following the planting year) ranged from 0.76 to 3.96 tons acre^{-1}. Variation within sites—even over the three nitrogen rates—generally was not as great as site-to-site variability.

Yields in these field settings did not reach the levels often observed in small plot studies recorded in the literature. During the first 3 years of production, yields at the Alabama and New York sites approached 4.5 tons acre^{-1}, but yields for the remaining sites were in the 1.8 to 3.1 tons acre^{-1} range. Yields also increased over the first few production years at most sites, but they were much more stable over time in Iowa and New York. In some cases, initial yields were hampered by weeds and other factors that negatively affected establishment. At one site, stand failure occurred over 2 consecutive years, likely due to residual herbicide in the soil that was not known to the researcher.

Averaged over nitrogen treatments, yields at most sites were in the 2.7 to 3.6 tons acre^{-1} range, but switchgrass responses to nitrogen were highly variable and appeared greatest in sites with low initial soil nitrogen. For example, in South Dakota and Virginia, the percent yield increase in response to nitrogen from the control to the highest nitrogen rate averaged 47% and 76% over all production years. In contrast, the average yield increase in Alabama (where some of the highest yields were recorded) was about 12%. In Oklahoma and New York, there was no benefit of added nitrogen over years, and in some production seasons, the effects of nitrogen on switchgrass in New York were significantly negative. The pattern of response in Iowa was unlike that at other locations in that the response to nitrogen was limited in the first few years of production, but by the fourth and fifth years, the response to nitrogen reached 52% and 88%.

Data from these studies provide greater understanding of the year-to-year and site-to-site variability in switchgrass production than is available with other research. The multiple years encompassed by this work also show the changes in production and nitrogen utilization that would not have been observable with shorter-term research. Data in the literature (largely from small plot studies) regarding switchgrass response to nitrogen are highly variable, and our data indicate that response to nitrogen occurs primarily on soils that are nitrogen limited. In addition, our data indicate that with soils of even moderate fertility, it may take several years of harvesting to reach a point at which response to nitrogen applications becomes economical.

Data regarding establishment costs have been analyzed for all sites, and a more complete analysis of yield responses to fertility over time is being finalized (Pease et al. forthcoming). As alluded to previously, initial data suggest responses to nitrogen may be of limited value, economically, unless the sites have limited soil nitrogen from the start. Key questions about the assumptions used in economic modeling must be addressed to determine the feasibility of switchgrass-to-bioenergy/bioproduct schemes. For example, land rental rates can vary widely within a given region depending on the cropping system; determining the appropriate value for land rent can be difficult, but it will be critical for arriving at appropriate economic assessment of energy cropping within a region.

Utility of marginal land for energy production systems also remains questionable, given challenges for establishment and that yields on marginal sites may be lower than desired. The establishment issues that cropped up at several sites in this study would have a negative influence on economic outcomes in a real-world setting and point to the further challenge for deploying biomass systems on marginal sites that may have difficult edaphic conditions, a seed bank laden with weed seeds, or both. Although manageable, these issues present additional costs in terms of lower yield with slow establishment or the cost of weed control. Of course, the value of a ton of switchgrass will remain the key driver for feasibility for marginal land use and fertilization.

Other questions affecting economic outcomes that could not be addressed by this research include factors such as harvest method, storage, and supply logistics. The large square and large round bales used for these systems could require very different field-to-factory storage and handling systems. These issues were beyond the scope of this research but have further economic implications for switchgrass to bioenergy/bioproduct systems.

From a project perspective, we have encountered few barriers. The Partnership has had a history of good leadership, and their communication and coordination with the research team has worked well. In the field, the research was faced with some initial crop failures, but all sites achieved adequate stands of switchgrass for the desired research.

From an industry perspective, as noted earlier, the economics behind these production systems will present the greatest barriers to development and deployment. Developing plant materials that are more productive on marginal sites may be an important next step for moving forward if marginal land is to be used for these systems.

Initially, data collection was challenged in part by the lack of stand establishment in Alabama (hence, we were only able to collect yield data over the last few years of the trial [i.e., 2012–2015]). In addition, greater yield potential would be expected from the Oklahoma site, had a southern lowland cultivar been available for planting at the start of the study. To address the issues of upland versus lowland switchgrass production in Oklahoma, we began a cooperation with a second site to gather some of the lowland production data. These data have been made available for the modeling efforts that are part of the Partnership. One of the challenges facing the modeling team is the limited data from sites on the periphery of the switchgrass production range.

Whether switchgrass response to nitrogen should have been the preferred treatment has been a question for our group at times. Other treatments that warrant exploration include use of species mixtures vs. monocultures, and there is a question regarding how best to extend harvest windows for these systems in order to reduce logistics costs.

While these questions are important, perhaps the most productive line of inquiry would involve the direct comparison of the various energy crops suited to a region. For example, both miscanthus and switchgrass are suited to many of the sites used in the feedstock partnership, but there is little assessment of their productivity in side-by-side trials. (This would be similar for sorghum, energycane, and other potential energy crops.)

Aside from stover and other crop residues, switchgrass remains the primary biomass feedstock of interest across much of the United States. This is due to its high productivity, broad adaptability, perenniality, and the crop’s high level of familiarity within the biofuel community. Although not part of this work, new switchgrass varieties have been developed or are in the development pipeline, and they promise to increase yields by several percentage units. Future work assessing these materials will be important for optimizing opportunities for the nascent bioenergy industry.

2.5 Key Outputs

2.5.1 Peer-Reviewed Manuscripts

Owens, V. N., D. R. Viands, H. S. Mayton, J. H. Fike, R. Farris, E. Heaton, D. I. Bransby, and C. O. Hong. 2013. “Nitrogen Use in Switchgrass Grown for Bioenergy across the USA.” *Biomass and Bioenergy* 58: 286–93. doi:10.1016/j.biombioe.2013.07.016.

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2.5.2 Presentations

Owens V. N., D. I. Bransby, R. Farris, J. Fike, E. Heaton, C. Hong, C. Hopkins, H. Mayton, R. Mitchell, and D. Viands. 2012. “Switchgrass Response to N Fertilizer across Diverse Environments in the U.S.” Presented at the 2012 National Sun Grant Initiative Conference, New Orleans, LA, October 2–5.

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Pease, J., J. H. Fike, V. Owens, R. Farris, E. Heaton, H. Mayton, and D. Viands. “Switchgrass N-response and Cost of Production on Diverse Sites.” *Biomass and Bioenergy* (forthcoming).

3. *Miscanthus x giganteus*

3.1 Description/Characteristics

Miscanthus x *giganteus* Greef & Deuter ex Hodkinson & Renvoize (hereafter "miscanthus") is a large-statured (up to 4 m in height), perennial grass (family: Poaceae). This sterile triploid hybrid was originally discovered in Japan in 1935, following a spontaneous mating between fertile diploid *M. sinensis* and tetraploid *M. sacchariflorus* (Hodkinson and Renvoize 2001). The hybrid was later introduced into Europe, the United States, and elsewhere as an ornamental landscape plant and a bioenergy crop. Miscanthus "Illinois," the clone chosen for this study, was obtained in 1988 from established plants at the Chicago Botanic Garden, vegetatively propagated, and planted in demonstration plantings at the University of Illinois (Maughan et al. 2012). It is named "Illinois" because the University of Illinois, Urbana-Champaign (UIUC) has conducted significant research using this clone.

This grass has been studied for its bioenergy potential in European trials since 1983 (Lewandowski et al. 2000) and in U.S. trials since the early 2000s (Heaton et al. 2004). Early results promised high biomass yields—up to 17.8 tons acre^{-1} in some European locations (Miguez et al. 2008), with mean yields of 9.8 tons acre^{-1} across European test sites (Heaton et al. 2004). Yields in the United States range from 2.0 to 15.6 tons acre^{-1} (Lee et al. 2014; Heaton et al. 2008). It is unknown whether field-scale plantings could reach these yields in the United States, particularly across varied environmental conditions, but the potential for high yields, at least in some locations, exists. Additional data are needed to compare years, regions/environments, and agronomic practices for miscanthus plantings in the United States.

3.2 Objectives

The objective of the project was to establish and manage replicated field trials of miscanthus to gather biomass production, yield response to fertility treatments, and sustainability data across five locations in the eastern and midwestern United States to assess its potential as a bioenergy feedstock.

The miscanthus Bioenergy Field Trials were part of the DOE-funded Regional Feedstock Partnership – Herbaceous Bioenergy Crop Field Trials. To evaluate miscanthus, collaborator sites through the central portion of the eastern half of the United States were selected. Once participants were identified, miscanthus plants were propagated at UIUC for distribution and planting at each site following a coordinated protocol. Collaborators were responsible for planting, managing, applying the research treatments, and collecting the data for the miscanthus field trial at their site. At each location, miscanthus was grown using a randomized, complete block design with three nitrogen fertility treatments (0, 53.5, and 107.1 lb acre^{-1}) replicated four times in 12, 10 m × 10 m test plots. Planting and harvest dates were recorded, along with soil type, environmental data (precipitation, temperature), soil fertility (nitrogen, phosphorous, potassium), and biomass yield and moisture content at harvest. Finally, the field trial data from each site were collected and assembled from all participants for analysis.

3.3 Methods

The five locations spanned 22° of longitude and 4° of latitude, representing a wide variety of environmental conditions (plant hardiness zones 5–7). At the initiation of the project in 2008, the five participating collaborators and research sites were the University of Nebraska, Mead, Nebraska; the University of Illinois, Urbana, Illinois; Purdue University, West Lafayette, Indiana; the University of Kentucky, Lexington, Kentucky; and Rutgers University, Adelphi, New Jersey (fig. 3-1). However, due to high miscanthus mortality and collaborator turnover, Purdue University dropped out of the study in 2009 and was replaced in spring 2010 by a Virginia Tech collaborator using a study site near Gretna, Virginia.

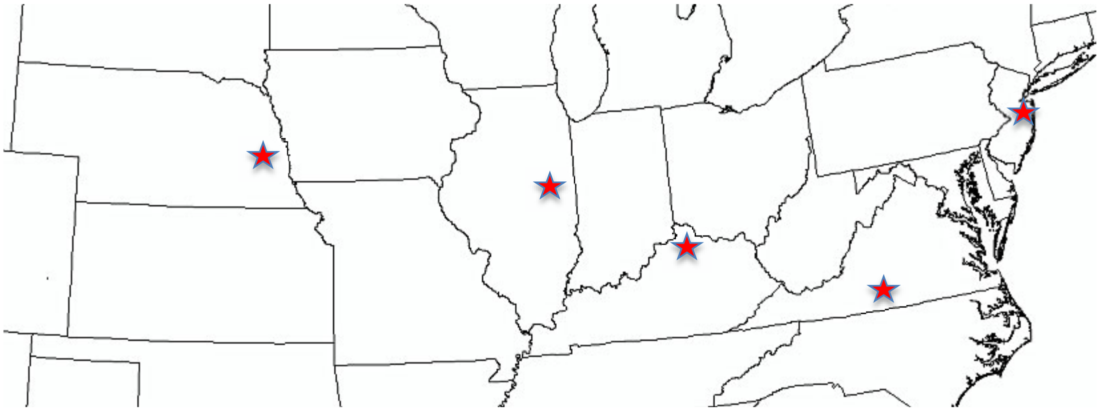

Figure 3-1 | Map showing Sun Grant Regional Feedstock Partnership *Miscanthus* x *giganteus* evaluation sites.

Because they are sterile, miscanthus cultivar plants were clonally propagated using rhizome fragments at UIUC and shipped to collaborators for planting. Although several related miscanthus varieties have now been developed and tested (e.g., “Amuri,” “Freedom,” and “Nagara”), the Partnership chose the “Illinois” clone because the UIUC has grown it for almost 30 years, and it is the most commonly available type being grown across the United States. This clone shows promise, yet its cold tolerance and response to nitrogen fertilizer are variable (Maughan et al. 2012).

The soil at the Illinois site is classified as a very deep, moderately well-drained Dana silt loam (fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) and a very deep, poorly drained Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls); the upper 30 cm of soil is dominated by a sandy loam. At Kentucky, the soil is classified as very deep, well-drained Maury silt loam (fine, mixed, active, mesic Typic Paleudalfs) and a Bluegrass silt loam (fine-silty, mixed, active, mesic Typic Paleudalfs). At Nebraska, the soil is classified as a very deep well-drained Tomek silt loam (fine, smectitic, mesic Pachic Argiudolls); however, this specific site is dominated by a silty clay loam soil texture. At New Jersey, the soil is a Holmdel sandy loam (fine-loamy, mixed, active, mesic Aquic Hapludults) with a restrictive soil layer or a bedrock layer between 50 cm and 80 cm in depth, depending on the plot. At Virginia, the soil is a very deep, well-drained Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults). Being predominantly sandy, the Illinois and New Jersey soils were less fertile and held less water than the soils at the other sites.

3.4 Results/Outcomes

Yields at four of the five locations have not differed substantially, with average yields across all years (2009–2014) and all fertility treatments of 7.2, 6.9, 6.6, and 6.6 dry tons acre^{-1} for Kentucky, Illinois, New Jersey, and Virginia, respectively. The average yield across all years (2009–2014) and all fertility treatments in Nebraska, however, was greater at 9.9 dry tons acre^{-1}. The average yield across all sites and all years (2009–2014) was 7.4 tons acre^{-1}.

In Kentucky and Nebraska, fertilization has not had an effect on yield in any year, while in Illinois, in 2012, 2013, and 2014; New Jersey in 2013; and Virginia in 2014, the yields of the 0 lb N acre^{-1} rate were less than the yields of the 53.5 and 107.1 lb N acre^{-1} rates. In these cases, fertilization improved yields; however, the higher rate of fertilization did not improve yields. In New Jersey, fertilization did not affect yields from 2009–2012; in 2013 (as noted above), yield increased with fertilization. It was only in 2014 that the yields were higher, with the higher 107.1 lb N acre^{-1} fertilization rate, than the other two lower fertilization rates. The need for fertilization of miscanthus was found to be very site specific, and, in some cases, the results (increased yields) of fertilization were only apparent after several years of fertilization.

In most cases, the highest fertilization rate was correlated with slightly decreased yield relative to the moderate rate. Therefore, we can conclude that the 53.5 kg N acre^{-1} rate was sufficient to augment yield in some locations, and that any additional fertilizer could be unnecessary, not cost-effective, as well as potentially harmful to the surrounding environment due to leaching, runoff, and gas emissions.

In other locations, the moderate fertilization rate did contribute to increased yield. For example, in Illinois, the average yield of unfertilized plants was 4.7 dry tons acre^{-1} with all years pooled. This increased to 8.1 dry tons acre^{-1} with the addition of 53.5 lb N acre^{-1}. The highest fertilization treatment resulted in average yields of 7.9 dry tons acre^{-1}. This pattern was similar in New Jersey and Virginia.

Yields differed from year to year at the same site with 2009 yields being consistently lower than subsequent years (2011 for Virginia). Across sites, 2012 was a lower-yielding year due to the severe drought in much of the study region. Most sites rebounded to pre-drought yields in 2013, with the exception of Nebraska and New Jersey; however, New Jersey recovered by 2014.

This study did not specify particular yield goals, but consistent, sustainable annual yields (i.e., yield stability) of the range of 8.9–9.8 tons acre^{-1} (after an establishment year), which would be desirable. Our study indicated that this is possible in some locations, especially with a moderate fertilization treatment, so long as water is not limiting.

Although early reports suggested miscanthus does not require nitrogen fertilizer, we would now recommend nitrogen amendment when the crop has not established well, when it has developed poorly, when density is low, when the crop is yellow, and/or when productivity is below reasonable expectations. This study has also reinforced our thoughts about where miscanthus should be produced—in the central United States where annual precipitation averages about 30 inches per year.

A number of studies have indicated that miscanthus can be grown sustainably, particularly compared with other crops. For example, methane and N_2O emissions have been found to be negligible for miscanthus production fields, although N_2O increased slightly with nitrogen fertilizer (Davis et al. 2014; Behnke et al. 2012; Drewer et al. 2012; Gauder et al. 2012). Nitrate leaching has also been found to be minimal or nonexistent in miscanthus production fields (Lesur et al. 2014), but the addition of nitrogen fertilizer was associated with increased nitrate leaching and increased N_2O emissions in the present study (Davis et al. 2014; Behnke et al. 2012). GHG emissions (in tonnes of CO_2 equivalents) from combusted miscanthus were significantly lower than combusted peat moss (Finnan et al. 2012), oil (Wang et al. 2012), and coal (Sanscartier et al. 2014). Miscanthus has sequestered carbon in plant tissues and soils (Zimmerman et al. 2012; Mishra et al. 2013).

This project led to synergistic activities with the British Petroleum-funded Energy Biosciences Institute (EBI), including the organization of an annual EBI-hosted feedstocks symposium and on-farm outreach activities at the EBI Energy Farm. The project was represented at the University of Kentucky Field Day and the Association of Applied Biologists conference in 2011. Through these activities, we educated thousands of international researchers and students about the use of miscanthus.

Although this project was successful in that we achieved what we set out to do and generated new information on yield and agronomic practices for miscanthus, it would have been improved with additional miscanthus genotypes, a greater number of study locations across a larger range of both longitude and latitude, and a longer duration.

Going forward, it will be important to discover whether yields can be improved further with other fertilizers, particularly phosphorus and potassium. Virtually nothing is known about the effects of these nutrients on miscanthus growth and yield. In addition, it will be useful to evaluate additional genotypes in a similar experimental design. Other genotypes have been developed, but they have not been grown and compared in this way. As previously mentioned, adoption of this crop is hindered by its difficult propagation process. Development of an inexpensive, reliable method of propagation, e.g., New Energy Farms Crop Expansion Encapsulation and Drilling System (CEEDSTM; newenergyfarms.com/products/ceeds/), will improve scale-up efforts and crop budgets. It will be important to understand disease or insect issues at commercial scale, although there are no reported problems with these issues in Europe, where some miscanthus has been commercially produced.

Lastly, miscanthus lags behind switchgrass in terms of its versatility. Switchgrass applications include bioenergy, bedding, wildlife conservation, hay, reclamation, and combustion. Switchgrass can also be used as an absorbent material for saltwater and other byproducts from fracking. It is likely that development of additional miscanthus bioproducts can only improve the market for miscanthus.

Some of the initial enthusiasm for miscanthus has waned recently—even with agronomic improvements—due to lags in the development of efficient ethanol-conversion technologies and an increased availability of natural gas from fracking and other extraction methods. New genotypes are being developed and trialed at UIUC, the University of Guelph, and elsewhere, but these are unlikely to be commercially available in the near future.

3.5 Key Outputs

3.5.1 Peer-Reviewed Manuscripts

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Davis, M. P., M. B. David, T. B. Voigt, and C. A. Mitchell. 2014. “Effect of Nitrogen Addition on *Miscanthus* x *giganteus* Yield, Nitrogen Losses, and Soil Organic Matter across Five Sites.” *Global Change Biology Bioenergy* 7 (6). doi:10.1111/gcbb.12217.

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3.5.3 Workforce Development

This project has funded three students who have completed University of Illinois graduate degrees, and a fourth, Miriam Molina, is scheduled to complete her Master of Science in early 2016. Several undergraduates and research specialists have also worked on this project.

3.6 References

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4. Sorghum

4.1 Description/Characteristics

Of the herbaceous bioenergy crops identified by DOE, sorghum is unique as it is a drought-tolerant, annual crop established from seed that is readily tractable to genetic improvement (Rooney 2014). Sorghum possesses many traits that are valuable in a bioenergy crop, including high biomass yield potential, drought tolerance, established production systems, a sequenced genome, and its tractability to breeding and further improvement (Rooney 2007). In addition, sorghum is an annual crop established from seed that can be rotated with other crops, providing flexibility in response to fluctuating markets. Based on prior breeding history, sorghum has extensive genetic variation and is divided into end-use types that can be roughly categorized as grain, forage, biomass, and sweet sorghums.

Grain sorghum is used to produce ethanol in the United States, and ethanol yields from sorghum grain are identical to corn (Wang et al. 2008). Biomass sorghum is used for the production of structural carbohydrates, and they accumulate large amounts of biomass in part because they are photoperiod sensitive (PS), meaning they do not flower when grown in the long day environments of the temperate United States. Thus, they continue to accumulate vegetative biomass for a much longer growing period. This type of sorghum is designed as biomass feedstock for lignocellulosic ethanol conversion programs. Sweet sorghums contain a high fermentable sugar concentration in a juicy stalk that can be extracted and fermented directly into ethanol. After juice extraction, the bagasse can be used to make ethanol from fermentation of the cellulose and hemicellulose, or it can be burned to produce electrical power. The biomass and sweet sorghums are particularly conducive for bioenergy production since they do not directly compete with the demand for food or feed.

4.2 Objectives

The purpose of this research project was to determine the yield and stability of six different sorghum genotypes available in 2008 grown at seven locations in six different states over 5 years. The results establish the biomass yield potential for sweet, forage, and biomass sorghums in different production regions of the United States and their relative stability of production over years. The data will be used to determine the role, types, and environments in which sorghum is adapted and economically feasible.

4.3 Methods

Six sorghum genotypes were evaluated in seven environments over 5 years. The six genotypes evaluated were Graze All, a photoperiod-insensitive (PI) sorghum-sudan forage hybrid; Graze N Bale, a PS sorghum-sudan forage hybrid; TX08001, a PS bioenergy hybrid; M81-E, a moderately PS sweet sorghum variety; Sugar T, a moderately PS sweet sorghum silage hybrid; and 22053, a moderately PS brown midrib (bmr) silage hybrid. TX08001 was developed by Texas A&M AgriLife Research; M81-E was developed in Mississippi by the ARS; and the remaining four hybrids are produced and marketed by Advanta Inc., primarily as forage sorghums for silage, green chop, grazing, and hay.

The seven locations used for testing were: Manhattan, Kansas; College Station, Texas; Corpus Christi, Texas; Ames, Iowa; Lexington, Kentucky; Raymond, Mississippi; and Roper, North Carolina (fig. 4-1). All yield trials were rain-fed; no supplemental irrigation was used in any location. In all locations and years, trials were planted in a randomized complete block design, but plot size ranged in size from 0.01 acres to 0.25 acres per plot, and there were either three or four replications due to space availability and management capacity. Standard production practices specific to each location were observed for fertilizer, tillage, and herbicide application. Target plant densities were 50,600 plants acre^{-1} for the sweet sorghums (Sugar T and M81-E); 60,700 plants acre^{-1} for the bioenergy types (22053 and TX08001); and 80,900 plants acre^{-1} for the forage sorghums (Graze All and Graze N Bale). Agronomic traits evaluated at each location were fresh weight, moisture concentration of the biomass, dry weight, and brix. Biomass samples were collected at harvest and dried in a forced air oven for a minimum of 72 hours to obtain the moisture content and dry weights.

Figure 4-1 | Map showing Sun Grant Regional Feedstock Partnership energy sorghum evaluation sites.

4.4 Results/Outcomes

The seven locations represented very different adaptation zones, and as expected, they varied widely in annual rainfall, seasonal temperature, and length of growing season. Furthermore, within the years tested (i.e., 2008–2012), rainfall varied widely from year to year and from location to location. The worst environment was 2009 in Corpus Christi where it was too dry to even plant the trial. In 2011, in both College Station and Corpus Christi, the rainfall was sufficient to plant but insufficient to sustain season-long growth, which resulted in significantly lower yields in those particular environments.

The majority of the variation observed in the data in this experiment was attributed to environmental effects (year, location, and year by location). Thus, breeding efforts for bioenergy sorghum might best be conducted on a regionalized basis. This conclusion is confirmed by the significant genotype by environment variation. The significant effect due to genotype for each trait indicates that there is considerable variation in sorghum that can be used to breed improved varieties and hybrids for ethanol production.

Across all environments, significant differences were detected among locations for each agronomic trait evaluated. Across environments, mean dry yield ranged from 3.2 tons acre^{-1} in Corpus Christi to 7.8 tons acre^{-1} in North Carolina. Lowest average yields were in the regions traditionally associated with lower rainfall (Texas and Kansas). Grain and forage sorghum are common in these regions because they are drought tolerant. Alternatively, the locations in the southeastern United States (Mississippi, North Carolina, and Kentucky) had greater yields for fresh weight and dry weight due to longer growing seasons, greater rainfall, and the adaptation of sorghum genotypes to warmer climates. Thus, while sorghum is quite capable of surviving periods of drought, the results indicate that the greatest yields occur in environments with consistently greater rainfall (Gill et al. 2014).

Variation from year to year demonstrates the effect of climate on productivity. For example, the 2011 season was dry for much of the southern United States, resulting in the lowest mean fresh and dry weights of any year in the study. In 2009, ample rainfall throughout most of the growing area produced the greatest mean fresh and dry weights of any year. These results confirm the importance of consistent and timely rainfall when determining where lignocellulosic ethanol production from sorghum is potentially feasible.

While both yield and composition are considered important in biomass sorghums, the inconsistency among potential processors makes it difficult to define the optimum composition for a biomass sorghum. Thus, biomass yield becomes the defining factor as to the best hybrids for production. Across these tests, the hybrid TX08001 produced the greatest mean fresh and dry weights. Productivity varied from year to year within an environment. For example, in College Station, Texas, between 2009 and 2012, the dry weight yield of TX08001 ranged from 1.9 to 9.3 tons acre^{-1}. The primary variable affecting yield was moisture, so less variation in yield was observed in more southeastern testing sites.

The results of this study also indicate that biomass sorghum is very difficult to dry in the field. In this study, differences in moisture content existed among the entries. However, TX08001 had the lowest average moisture content, ranging from 65% to 75% at harvest. Unlike forage sorghums that are commonly dried and baled, biomass sorghums have significantly thicker stems and are harvested relatively later in the season; both of these factors are less conducive for dry down. Consequently, processors who use sorghum will likely have to adopt systems that handle wet biomass. While the additional moisture increases transportation costs, the water in the sorghum genotypes tested in this trial contains substantial amounts of fermentable sugars, which do represent another processing stream, much like energycane.

The results of this study confirm that sorghum can produce sufficient biomass yields to meet the needs of a developing biomass industry. The tractable genetics of sorghum coupled with established breeding systems will allow great strides to be made in the productivity of future high-biomass sorghum. In fact, since this research was conducted, several companies have commercialized sorghum hybrids cultivars specifically for the energy market. While forage and grain sorghums have been traditionally grown in the southern and central regions of the country, energy sorghums produce the highest and most consistent yields in the southeastern United States. The large amount of variation due to the effects of environment and genotype by environment highlights the need for and value in breeding specifically for the target area. With the proper genotypes and production environments, sorghum will be a valuable tool in the goal of sustainably producing 1 billion tons of dry biomass each year in the United States.

4.5 Key Outputs

4.5.1 Peer-Reviewed Publications

Gill, J. R., P. S. Burks, S. A. Staggenborg, G. N. Odvody, R. W. Heiniger, B. Macoon, K. J. Moore, M. Barrett, and W. L. Rooney. 2014. “Yield Results and Stability Analysis from the Sorghum Regional Biomass Feedstock Trials.” *Bioenergy Research* 7 (3): 1026–34. doi:10.1007/s12155-014-9445-5.

Hoffmann, L., Jr., and W. Rooney. 2014. “Accumulation of Biomass and Compositional Change over the Growth Season for Six Photoperiod Sorghum Lines.” *BioEnergy Research* 7 (3): 811–15. doi:10.1007/s12155-013-9405-5.

Mullet J., D. Morishige, R. McCormick, S. Truong, J. Hilley, B. McKinley, R. Anderson, S. Olson, and W. Rooney. 2014. “Energy Sorghum—A Genetic Model for the Design of C4 Grass Bioenergy Crops.” *Journal of Experimental Botany* 65 (13): 3479–89. doi:10.1093/jxb/eru229.

Olson, S. N., K. Ritter, J. Medley, T. Wilson, W. Rooney, and J. E. Mullet. 2013. “Energy Sorghum Hybrids: Functional Dynamics of High Nitrogen Use Efficiency.” *Biomass and Bioenergy* 56: 307–16. doi:10.1016/j.biombioe.2013.04.028.

Packer, D. J., and W. L. Rooney. 2014. “High Parent Heterosis for Biomass Yield in Photoperiod-Sensitive Sorghum Hybrids.” *Field Crops Research* 167: 153–8. doi:10.1016/j.fcr.2014.07.015.

Rooney, W. L. 2014. “Sorghum.” In *Cellulosic Energy Cropping Systems*, edited by D. Karlen, 109–29. London: Wiley and Sons. doi:10.1002/9781118676332.

4.5.2 Programmatic Reports (Peer-Reviewed)

McLaughlin, W. A., E. Rister, R. D. Lacewell, L. Falconer, W. Rooney, D. McCorkle, and J. Blumenthal. 2013. “The Economic and Financial Implications of Supplying a Bioenergy Conversion Facility with Cellulosic Biomass Feedstocks.” College of Agriculture, Auburn University and Texas A&M AgriLife. http://www.ag.auburn.edu/biopolicy/documents/Economic%20&%20Financial%20Implications%20of%20Supplying%20a%20Bioenergy%20Conversion%20Facility%20with%20Cellulosic%20Biomass%20Feedstock.pdf.

4.5.3 Conference or Symposium Proceedings/Seminars

Gill, J. R., W. L. Rooney, P. S. Burks, S. A. Staggenborg, G. N. Odvody, R. W. Heiniger, B. Macoon, K. J. Moore, M. Barrett, and J. F. Pedersen. 2012. “Agronomic Results from the Sorghum Regional Biomass Feedstock Trial.” In *Proceedings from Sun Grant National Conference: Science for Biomass Feedstock Production and Utilization,* Vol. 1, Ch. 2.10. New Orleans, LA, October 2–5. https://ag.tennessee.edu/sungrant/Documents/2012%20National%20Conference/ConferenceProceedings/Volume%201/Vol1final.pdf.

Owens, V. D., K. Lee, T. Voigt, and W. Rooney. 2009. “The Regional Biomass Feedstock Partnership: Herbaceous Energy Crops and CRP Land for Biomass Production across Environmental Gradients.” In *Proceedings from 2009 World Congress on Industrial Biotechnology and Bioprocessing*. Montreal, Quebec, Canada: Biotechnology Industry Organization.

4.6 References

Gill, J. R., P. S. Burks, S. A. Staggenborg, G. N. Odvody, R. W. Heiniger, B. Macoon, K. J. Moore, M. Barrett, and W. L. Rooney. 2014. “Yield Results and Stability Analysis from the Sorghum Regional Biomass Feedstock Trial.” *Bioenergy Research* 7 (3): 1026–34. doi:10.1007/s12155-014-9445-5.

Rooney, W. L. (2014) “Sorghum.” In *Cellulosic Energy Cropping Systems,* edited by D. L. Karlen. Chichester, UK: John Wiley & Sons, Ltd. doi:10.1002/9781118676332.ch7.

Rooney, W. L., J. Blumenthal, B. Bean, and J. E. Mullet. 2007. “Designing Sorghum as a Dedicated Bioenergy Feedstock.” *Biofuels, Bioproducts and Biorefining* 1: 147–157. doi:10.1002/bbb.15.

Wang, D. S., S. Bean, J. McClaren, P. Seib, R. Madl, M Tuinstra, Y. Shi, M. Lenz, X. Wu and R. Zhao. 2008. “Grain Sorghum Is a Viable Feedstock for Ethanol Production.” *Journal of Industrial Microbiology Biotechnology* 35 (5): 313–20. doi:10.1007/s10295-008-0313-1.

5. Energycane (*Saccharum* spp.)

5.1 Description/Characteristics

Sugarcane is bred for large stalk diameter, low fiber content, and high sugar content under Louisiana conditions. However, the northern limits of these sugarcane varieties have always been determined by the tropical origins of their parents, which constrains the crop in the United States to southern Louisiana, south of Lake Okeechobee in Florida, and the southern tip of Texas. During the 1960s, mosaic virus threatened the sugarcane industry in Louisiana. USDA's ARS at Houma imported wild cane (*Saccharum spontaneum*) from the Himalayas and screened it for resistance to mosaic virus (Anna Hale, pers. comm.). Along with the mosaic virus resistance from the *S. spontaneum* parent, there was cold tolerance. During the "oil shocks" of 1973 and 1979, Louisiana State University selected hybrid progeny of sugarcane x *S. spontaneum* for biomass yield and high fiber content, releasing variety L79-1002—a cane specifically released as a biomass feedstock (Bischoff et al. 2008). Because *S. spontaneum* has a high fiber stalk (woody), the "energycane" progeny have a corresponding reduction in sugar concentration (usually <11%), making it unattractive to the sugar industry. USDA's ARS Sugarcane Research Unit at Houma continued a small program on energycane development throughout the 1990s, but added cold hardiness to the list of desirable traits. In fall of 2007, Drs. Tew and Richard sent billets of 11 genotypes to Mississippi State University (Starkville, Mississippi) for general assessment and winter hardiness screening. Five genotypes were deemed suitable for continued testing at latitudes north of New Orleans, Louisiana (Baldwin, unpublished data).

Energycane, like sugarcane, is a tropical perennial that is vegetatively propagated. A crop can be harvested, and the subsequent year's crop grows back from the surviving crown. The regrowth after the first harvest is called the first ratoon; after the second harvest, the second ratoon, etc. Unlike most other warm-season (summer) crops, energycane is established in the fall from mature canes of existing plants. Because energycane is vegetatively propagated, vigor observed in filial 1 (F_1) hybrids of the sugarcane x *S. spontaneum* cross is maintained from field to field since all subsequent plantings are from the original vegetative material.

Establishment of a field follows the same process as commercial sugarcane. Mature canes (seedcane) of the desired genotype are harvested in August/September. The apical meristem is removed to stimulate shoot growth from lower nodes. New fields are plowed to create beds and furrows. Canes are placed horizontally in the furrow overlapping by one-third, and the soil from the bed is cast down over the canes to bury them. In roughly 2 to 3 weeks shoots emerge. These shoots are killed by fall frost, but the cane and crown of the new shoots remain protected underground. In spring, new shoots emerge and will grow through the summer. Being tropical in origin, energycane doesn't undergo a natural senescence. Growth slows in the fall because of cooler temperatures, but a killing frost is required to stop growth. Failing natural senescence, a frost-kill traps nutrients in the aboveground plant parts. Removal of this material removes the minerals trapped in it. Immediately following the killing frost, moisture levels initially rise in the plant (root pressure keeps water flowing into the plant, but there isn't transpirational loss). Thus, harvest is made on "wet" material (60%–70% moisture), altering preservation/storage requirements. Unlike switchgrass and giant miscanthus, which can be baled, energycane must be consumed directly from the field or ensiled anaerobically for storage.

5.2 Objectives

The objective of the energycane field trials in this project was to evaluate energycane hybrids for biomass yield. We established replicated field trials of five genotypes (Ho 02-144 & 147; Ho 06-9001 & 9002; and Ho 72-114) common to all seven locations across five states (Georgia, Hawaii, Louisiana, Mississippi, and Texas) to evaluate the potential production and sustainability of energycane as a bioenergy feedstock (fig. 5-1). Additionally, it is desirable to know the duration of productivity of a plant stand (i.e., stand persistence).

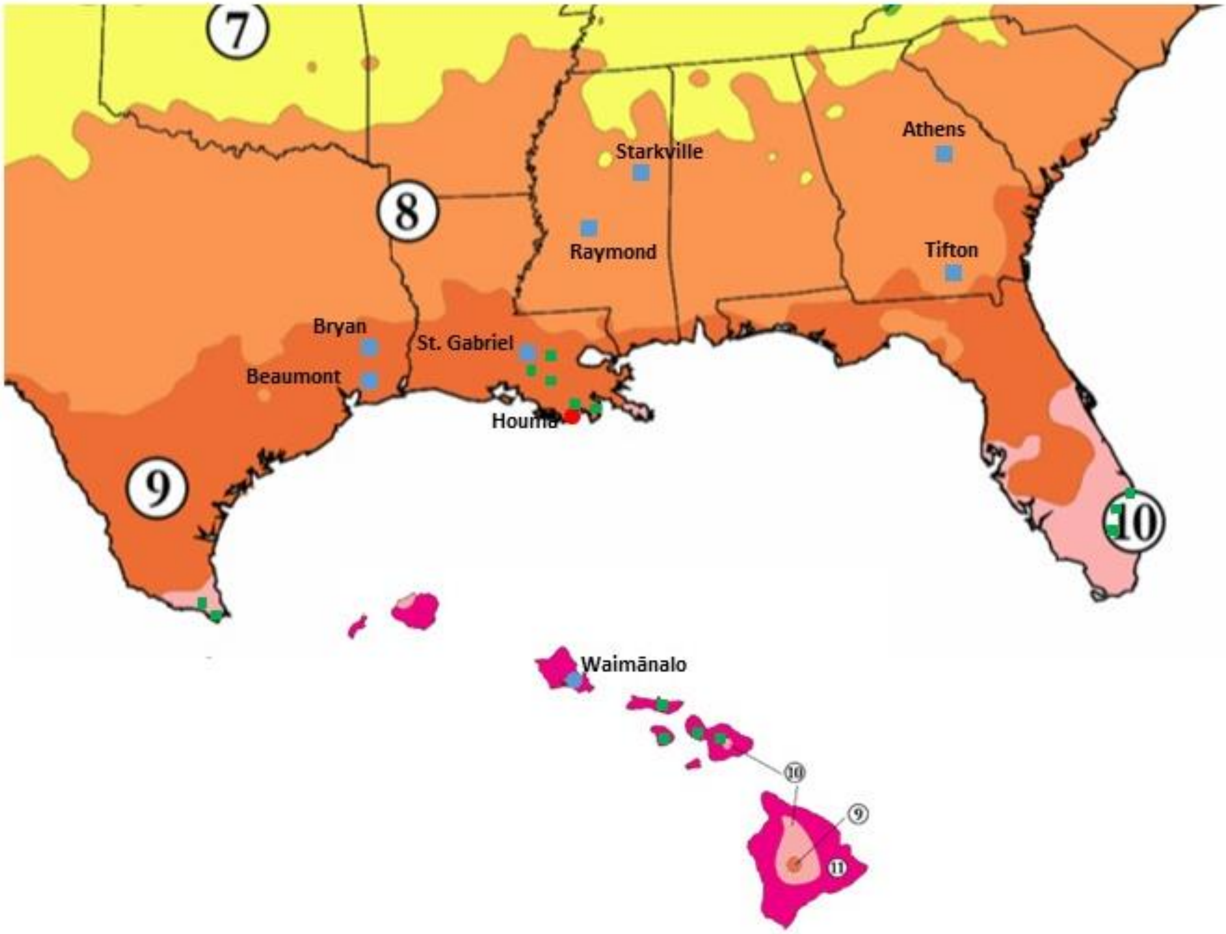


Figure 5-1 | Location of participants for the Energycane Herbaceous Feedstock Partnership. Green squares indicate locations of commercial sugarcane production. Energycane test sites (blue dots) are plotted on the USDA hardiness zone map (planthardiness.ars.usda.gov/PHZMWeb/Maps.aspx). Houma, Louisiana, (red dot) is the source of all germplasm used in this testing.

5.3 Methods

Five energycane lines tested from 2006–2008 at Starkville, Mississippi, were selected for broader testing across the Southeast and Hawaii as part of the Partnership. These genotypes were: Ho 02-147, Ho 02-144, Ho 72-114, Ho 06-9001, and Ho 06-9002. In August and September of 2008, seed cane was distributed to seven test sites (Tifton, Georgia; Auburn, Alabama; Raymond and Starkville, Mississippi; St. Gabriel, Louisiana; Beaumont and College Station, Texas) (fig. 5-1). Crop failure at the Auburn site caused an alternate site to be selected at Athens, Georgia, planted in 2009. Waimānalo, Hawaii, was also added in 2009, but planting was delayed a year due to quarantine. Little was known concerning the area of adaptation and cold hardiness of this germplasm. Athens, Georgia, and Starkville, Mississippi, were the most northern locations (33° North latitude). Planting was accomplished at all locations within three days of seed cane delivery. Some sites included other sugar or energycane genotypes, but all locations had the same five genotypes in common. Because seed cane germplasm was in short supply, field size was limited. Individual genotypes were planted in plots 30 ft long × three 18-ft wide rows. Two rows would be harvested for yield estimates; the third would be used for growing season data. Plots of all five genotypes occupied a space 30 ft x 96 ft; this was replicated four times within a field at each location. During the following spring (2009), emergence data (shoots/plot), date of 50% emergence, and soil temperature at 6 in was monitored. Over the course of the growing season, mean height and °Brix (a measure of soluble carbohydrates in the sap) were recorded. Site scientists recorded major factors potentially impacting yield (drought, hurricanes, and extremes of temperature, insects, or disease). Harvest date varied by location, depending on frost date and weather conditions. At the end of each growing season, stalk count, final mean height, a general frost damage rating, final ºBrix, and fresh harvest weight were recorded. From the sacrifice row, sap yield, stalk moist weight (after pressing sap out), and dry weight were recorded. Dry stalks were ground and submitted for structural carbohydrate analysis (cellulose, lignin, and sugar). During summer 2015, the continental sites were in their sixth ratoon crop (7 years of data). Hawaii reported its fourth ratoon crop after the 2014 growing season.

5.4 Results/Outcomes

As expected, most characteristics varied by variety and location. Height of all germplasm increased throughout the summer into the fall. Height measurements indicated onset of “grand growth” (the point at which growth accelerates rapidly) occurred in June or July. The date of onset differed for each of the sites; regardless of location or year, it corresponded to a mean ambient air temperature of 86° Fahrenheit. Grand growth ceased (heights remained level) after mid-September, which corresponds to daytime temperatures cooling below 86° Fahrenheit. Because of the longer growing season, plant height and, generally, plant yield were greater at southern locations compared to northern locations, with the exception of Bryan, Texas; there, lack of rainfall limited height of germplasm. ºBrix varied by location, variety, weather, and time of growing season. ºBrix values at all locations dropped substantially 2 weeks after frost, but remained relatively stable thereafter, presumably due to cooler temperatures. Germplasm differences for ºBrix were not uniform across locations, indicating some genotypes accumulated more sugar at a given location, while others accumulated more sugar at a different location. Efforts to extract sap varied by variety also; Ho 02-144, Ho 06-9001, and Ho 06-9002 had less extractable sap than Ho 02-147 and Ho 72-114. The difference is due to the woody nature of the former (backcrosses to *S. spontaneum*) and the pulpy nature of the latter varieties.

With regard to biomass production, dry matter yield is the most important attribute. Of the seven locations in 2009 (the first year), highest yields were observed at Tifton, Georgia, and Beaumont, Texas. This was followed by Raymond, Mississippi, and St. Gabriel, Louisiana. Lowest yields were observed at the two most northern sites: Athens, Georgia, and Starkville, Mississippi. Third-year yields included data from the site at Waimānalo, Hawaii, for the first time. Hawaiian law prohibited the importation of sugarcane germplasm (repealed), and heat treatments to destroy pathogens delayed establishment of their test. Mean yields at Bryan, Texas, and St. Gabriel, Louisiana, were 22.3 tons acre^{-1}. The general trend was toward increasing yield at all locations with the exception of Athens, Georgia, which suffered damage to the stand from a record cold winter. There were strong reductions in yield at Beaumont, Texas, due to drought conditions. Hawaii’s yields for the five common energycane varieties had a mean of 16.5 tons acre^{-1}, similar to Tifton, Georgia, and Beaumont, Texas, but less than Bryan, Texas. It is important to note that this was Waimānalo’s first year of growth, and that is being compared to sites on the mainland in their third year of growth.

During the second and third ratoon crops, yields started to decline, with the exception of the Raymond site (which always had modest yields). This decline coincides with observations in sugarcane fields suggesting a maximum of 3 to 4 productive years before replanting is necessary. It should be noted, if the test had not continued into 2014 (fifth ratoon crop), yield drops would not have been noticed at Starkville, Mississippi, nor Athens, Georgia.

At the more northern locations, extremely cold winters limited production. However, these locations allow the breeders at USDA's ARS at Houma to differentiate between lines that are more cold-hardy than others. The presence of potentially troublesome insects, sugarcane borer (*Diatraea saccharalis*) and Mexican rice borer (*Eoreuma loftini*), was reported at Beaumont, Texas, and Raymond, Mississippi—though it was more problematic on sweet sorghum at Raymond. Sugarcane smut (*Sporisorium scitaminea*) was reported at Tifton, Georgia, in 2011, but only in a single variety (L79-1002), which was not part of the five genotypes common to all locations. Discussion among scientists has raised the potential concern that growing energycane across the entirety of the South would provide pests from western cane areas a migration route to Florida production areas.

In summary, the new germplasm/varieties tested in this work have shown that energycane can produce 10–11 dry tons acre^{-1} yr^{-1} yields at the most northern locations (33° North latitude) and in excess of 20 dry tons acre^{-1} yr^{-1} at the southern locations. However, at locations from Raymond, Mississippi, north, other biomass crops produce similar or greater yields and don't require the specialized infrastructure for harvest and planting. For example, at the Starkville location, sweet sorghum, giant miscanthus, and lowland switchgrass were grown concurrently in fields adjacent to the energycane. Mean yields of each species were 12, 18, and 16 dry tons acre^{-1} yr^{-1}, respectively. Determination of acceptable production location is a function of species, environment, and competition by other species for the same markets.

5.5 Key Outputs

5.5.1 Peer-Reviewed Manuscripts

Knoll, Joseph E., William F. Anderson, Edward P. Richard Jr., Joy Doran-Peterson, Brian Baldwin, Anna L. Hale, and Ryan P. Viator. 2013. "Harvest Date Effects on Biomass Quality and Ethanol Yield of New Energycane (*Saccharum* hyb.) Genotypes in the Southeast USA." *Biomass and Bioenergy* 56: 147–56. doi:10.1016/j.biombioe.2013.04.018.

5.5.2 Outreach Publications

Rushing, J. Brett, D. Scott Horton, Brian S. Baldwin, and Edward Richard. 2008. "Evaluation of Energy Cane for Biomass Production in Starkville, MS." U. S. Department of Agriculture, Agricultural Research Service. http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=232723.

5.5.3 Proceedings

Baldwin, B., W. Anderson, J. Blumenthal, E. C. Brummer, K. Gravois, A. Hale, J. R. Parish, and L. T. Wilson. 2012. "Regional Testing of Energy Cane (*Saccharum* spp.) Genotypes as a Potential Bioenergy Crop." In *Proceedings for the Sun Grant Initiative National Conference*, Vol. 1, Ch. 1.4. New Orleans, LA: Southeastern SunGrant Center, October 2–5. http://sungrant.tennessee.edu/NR/rdonlyres/40B6A4BE-C9A0-4A32-BBD0-8D5A2CF0D436/3688/14Baldwin_Brian.pdf.

5.5.4 Presentations

Baldwin, B. S. 2010. “Biomass Energy Crops for the Southeast.” Presented at Michigan State University Biofuels Conference, Jackson, MS, August 11–13.

———. 2010. “Biomass for Bioenergy: Where the Industry Appears To Be Going.” Presented at Seventh Eastern Native Grass Symposium, Knoxville, TN, October 5–8.

———. 2012. “Factors Impacting Feedstock and Bio-Based Fiber Composition.” Keynote Presentation. Presented at the 2012 BioEnvironmental Polymer Society Conference, Denton, TX, September 18–21.

Baldwin, B. S., W. Anderson, J. Blumenthal, E. C. Brummer, K. Gravois, A. Hale, and L. T. Wilson. 2013. “Energycane (*Saccharum* spp.) Sugarcane Goes North.” Presented at 245th National Meeting of American Chemical Society, Carbohydrates Division: Special Session on Biofuels, Bioproducts, and Biomass from Sugar Feedstocks, New Orleans, LA, April 8.

Baldwin, B. S., W. Anderson, C. Brummer, J. R. Parish, K. Gravois, L. T. Wilson, J. Blumenthal, and A. Hale. 2013. “Southeast Regional Evaluation on Energy Cane (*Saccharum* spp.) Genotypes as a Potential Bioenergy Crop.” Presented at Southeastern Conference Symposium, Atlanta, GA, February 10–12. http://www.youtube.com/watch?v=nIkf8NZSzwc.

Baldwin, B. S., D. K. Lee, V. Owens, W. Rooney, and T. Voigt. 2009. “U.S. Dept. of Energy Regional Biomass Feedstocks Partnership.” Presented at 21st Annual Meeting for the Association of Advancement of Industrial Crops, Termas de Chillán, Chillán, Chile, November 14–19.

Baldwin, B. S., J. I. Morrison, J. D. Richwine, and J. B. Rushing. 2015. “Is Energy Cane a Viable Bioenergy Crop in North-Central Mississippi?” Presented at American Society of Agronomy, Southern Regional Branch Annual Meeting, Atlanta, GA, February 1–3.

Baldwin, B. S., J. B. Rushing, E. Richard, T. Tew, and A. Hale. 2010. “Energy Cane: Sugarcane Gone North.” Presented at Seventh Annual Bioenergy Feedstock Symposium, Champaign, IL, January 11–12.

Knoll, J. E., W. F. Anderson, B. Baldwin, and E. Richard. 2010. “Harvest Date Effects on Biomass Yield and Quality of New Energycane (*Saccharum* hybrid) Genotypes in the Southeastern USA.” Presented at American Society of Agronomy, Crop Science Society of America, Soil Science Society of America Annual Meeting, Long Beach, CA, October 31–November 4.

Morrison, J. I., and B. S. Baldwin. 2012. “Responsibilities with the Evolution of Land Use: Is the Bioeconomy Bad for Biodiversity?” Presented at Growing the Bioeconomy: Social, Environmental, and Economic Implications, Banff, Alberta, Canada, October 2–5, 64.

Owens, V. N., B. S. Baldwin, D. K. Lee, and T. B. Voigt. 2013. “Perennial Herbaceous Energy Crops and CRP Land for Biomass Production in the USA: A Five Year Regional Feedstock Partnership Report.” Presented at 10th World Congress on Industrial Biotechnology, Montreal, Canada, June 16–19.

Rushing, J. B., B. S. Baldwin, E. P. Richard, and T. L. Tew. 2009. “Evaluation of Cellulosic Energy Feedstocks for Production in Northcentral Mississippi USA.” Presented at 21st Annual Meeting of the Association for the Advancement of Industrial Crops, Termas de Chillán, Chillán, Chile, November 14–19.

5.5.5 Posters

Baldwin, B. S., R. Lemus, and D. Lang. 2011. “Grassy Feedstocks for Biomass Energy.” Poster presented at the Mississippi Biofuels Conference, Starkville, MS, October 5–7.

5.6 References

Bischoff, K. P., K. A. Gravois, T. E. Reagan, J. W. Hoy, C. A. Kimbeng, C. M. LaBorde, and G. L. Hawkins. 2008. “Registration of ‘L 79-1002’ Sugarcane.” *Journal of Plant Registrations* 2 (3): 211–7. doi:10.3198/jpr2007.12.0673crc.

Hale, A. 2012. Research Geneticist (Plants), Sugarcane Research Unit, 5883 USDA Rd. Houma, LA, 70360-5578.

6. Cereal Crop Residues

6.1 Description/Characteristics

For the purpose of this project, cereals included wheat, barley, oats, triticale, and rye, as well as sorghum and millet grown for grain. In the last decade, these cereals have been annually grown on more than 55 million acres in the United States. In the previous decade, the combined acreage was more than 80 million acres in some years. At first blush, cereals might appear to be an obvious source of biomass. Acreages were large and spread across the nation. These crops were typically harvested for their grain while plant stems and leaves (residues) were left in the field. There was a general sense that these "waste" residues could be easily collected and used as a source of biomass; however, cereal growers, researchers, and extension and agricultural professionals knew the rest of the story. The vast majority of cereal acreage was grown under dryland conditions in areas with low to moderate rainfall and in environments where harsh winter or summer drought conditions could dramatically affect crop yields. In addition, many cereal growers participated in government crop support programs that required them to leave crop residues in place for soil conservation purposes. Without support program changes, these growers could not harvest residues for biomass purposes.

6.2 Objectives

The objectives of the study were as follows:

A. Establish a cereal project group among interested cereals extension and research scientists across the United States.

B. Query this group as to existing long-term cereal production plots across the United States. The group will, in turn, query the managers of these plots as to their experiences with residue removal or addition in these plots. The question to be addressed is whether significant changes are expected in SOM or other soil characteristics with the removal of 50 or 100% of the straw in production areas where annual grain yields typically exceed 4,500 lb acre^{-1}. An American Society of Agronomy/Crop Science Society of America/Soil Science Society of American annual meeting symposium was proposed for 2009.

C. Using USDA NASS county average data, obtain and average available grain yield data for the past 5 years. Using the axiom that 100 lb of straw is produced for every 60 lb of grain (a harvest index of 38%, which is typical for wheat and barley), remove any area with a 5-year average grain yield of less than 4,500 lb acre^{-1} from further consideration. Areas with less than 4,500 lb acre^{-1} yield were excluded assuming 1,500 lb was needed for soil conservation purposes and at least 3,000 lb was needed for effective harvest.

D. Using geographic information system, plot areas of the United States where straw removal seems possible. In these areas, determine if there are grain plots. Ask scientists to gather harvest index data from current season plots. Economics of gathering, handling, and transporting straw was not considered in this evaluation.

E. Collect a small subset of straw samples from across the nation. Run these samples through the Idaho National Laboratory near-infrared analysis and determine if there are differences in composition among these samples.

6.3 Methods

The cereals group took a different approach to the overall DOE program goals of assessing biomass production capability in each of the crop systems, assessing sustainability of biomass removal in each system, and determining biomass supply curves. A significant amount of information was already available on cereal residues, as were data from long-term plots that had been established to assess the effect of residue levels on soil quality. The group made the decision to “mine” available information and trial work to address program goals versus conducting new trial work. The cereal residue group invested their funds in four activities:

A. *Mining long-term plot data for information on soil quality.* A number of long-term (50+ years) cereal production plots exist in the United States and around the world. The current managers of these plots were asked to query their available data to address the effect of residue removal on soil quality. Could they document effects on SOM or other soil characteristics with the removal of residues?

B. *Creating residue maps using existing data.* Using NASS county data, grain yields for a 10-year period were obtained. Using this data and harvest index values (the amount of residue produced for each unit of grain), it was possible to create cereal residue maps over a 10-year period for all areas of the United States where NASS data was available.

C. *Suggesting a revised harvest index value for wheat.* The historic wheat harvest index value was 38%. For every bushel of wheat (60 lb of grain) produced, it was predicted that 100 lb of residue was also produced [60/(100+60) = 38%]. Extension agronomists conduct cereal grain variety trials across the nation each year. Those cereal agronomists with interest were asked to determine the harvest index for their plots over a 2-year period. The intent was to determine if the harvest index for newer wheat varieties was, in general, similar to or different than the historic 38% value.

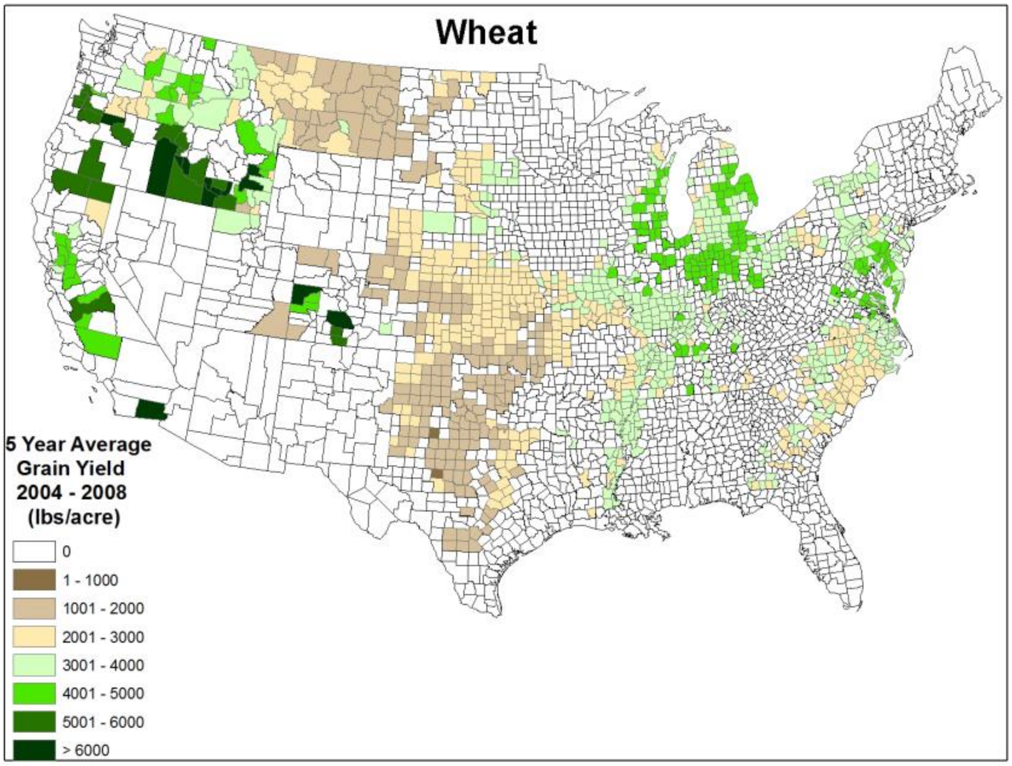
D. *Collecting sets of straw samples from across the nation for biomass quality assessment.* Those agronomists who conducted harvest index trials were asked to gather variety by site-specified straw samples and to send these for storage and possible analysis at Idaho National Laboratory.

6.4 Results/Outcomes

Mining long-term plot data for information on soil quality. The Partnership sponsored a symposium on the topic of long-term plots and residue levels on soil quality, which was held at the American Society of Agronomy meeting in Pittsburgh, Pennsylvania, in 2009. Seven papers were given as part of this symposium, and their findings were later published as a symposium series in *Agronomy Journal* (Huggins et al. 2011).

From these papers and from other work that addresses the amount of cereal residue that must be left in place for soil maintenance purposes, one can draw the general conclusion that, in most situations, at least 3,000 lb acre^{-1} of residue should be left on the ground. If mechanical harvest is then considered, agricultural engineers have estimated that at least 3,000 lb of residue must be available for collection for efficient harvest of the residue, resulting in a minimum residue yield of 6,000 lb acre^{-1} to sustainably and efficiently harvest the residue.

To assess the accuracy of the historic wheat harvest index value (0.38), a survey was conducted on the aboveground biomass, grain yield, and straw yield of 12 cultivars of durum wheat, 40 cultivars of hard red spring wheat, 14 cultivars of hard red winter wheat, 174 cultivars of soft red winter wheat, 3 cultivars of soft white spring wheat, and 12 cultivars of soft white winter wheat in eight states (Arizona, Idaho, Kentucky, Minnesota, North Dakota, Oklahoma, Oregon, and Texas) of the United States from 2008 to 2010 (Wiersma et al. 2016). Across all wheat classes and locations, the harvest index ranged from 0.33 to 0.61, with an average of 0.45. By combining the minimum residue yield required for harvest (6,000 lb acre^{-1}) with the updated, more realistic harvest index (0.45), a “net available” residue map should only include those areas of the United States where, using wheat as our surrogate, yields exceed 82 bu acre^{-1} (82 bu × 73 lb straw per bu with a harvest index of 0.44 = 6,013 lb straw acre^{-1}; if a higher harvest index is used, then an even higher bushel-per-acre yield is needed to reach the 6,000-lb residue level). If a minimum 6,000-lb value is used, this narrows areas available for wheat residue harvest to several dozen across the country, at most.



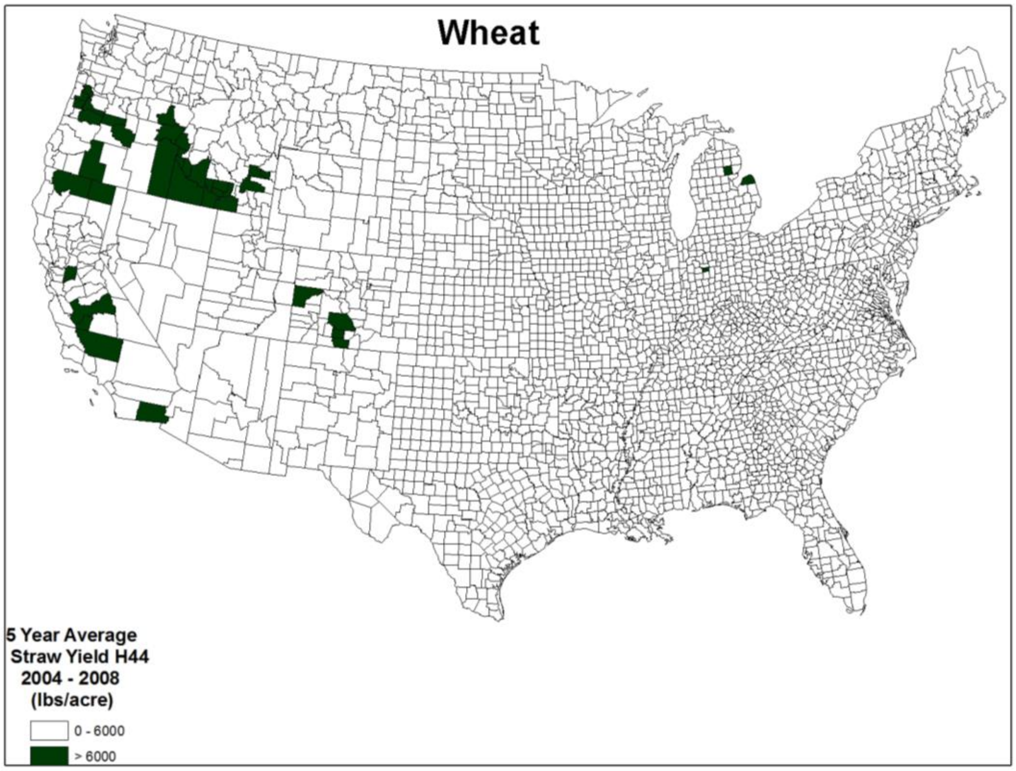


Figure 6-1 | Five-year average wheat yields (top) for the period 2004–2008, and potential straw yield (bottom) using a harvest index value of 44%. The green areas in the bottom map are counties where straw yield would exceed

6,000 lb acre^{-1} and, therefore, where it may be possible to consistently use wheat straw as the sole source for a biofuel plant.

Creating residue maps using existing data. NASS county data was used to create grain yield maps and predicted straw yield maps using harvest index values. Maps for the 1999–2008 time period for barley, oats, rice, sorghum, wheat, and a combined straw total can be found on the Oregon State University website (sungrant.oregonstate.edu/projects/cereal-residue). Maps have been generated that show areas of the United States in which either a 5- or 10-year period predicted straw yields that exceeded 6,000 lb—our suggested minimum harvest level. Reliable straw supplies would be essential for establishment of biomass processing plants. When looking at these maps, based on the assumptions made in these assessments, you will see that despite the vast acreages and widespread production of cereal crops, there are few predicted locations for reliable biofuel production if cereal residues are used as the sole source of biomass. A few sample maps are shown in figure 6-1.

Collecting sets of straw samples from across the nation for biomass quality assessment. Several hundred straw samples were collected from existing variety testing plots for use in determining harvest index values. Collected samples were from common cereal check cultivars and from the most promising experimental lines. These samples have been cataloged and are in storage at Idaho National Laboratory for use in cereal residue biofuel potential assessments.

Site-specific information will be the key to using cereal residues as a biomass source for biofuel production. Site-specific management information and technologies, as opposed to “clear cut” strategies, may open residue harvest options. Differential harvest in fields on a real-time basis is now possible. Straw balers can be attached directly to combines, and grain yield sensing technologies could be used to allow baling of those areas of a field where straw loads are adequate to support both soil health and straw harvest. In areas where grain yields are high but not quite high enough to allow for every-year harvest of straw, differential harvest among fields over time may allow consistent biomass harvest in that area.

Another spinoff of this research effort is that companies like Pacific PowerStock have directly used some of the mapping procedures developed as part of this project to do biomass assessments across the nation (pacificpowerstock.com).

Cereal residues will be a part of the biomass and biofuels future of the United States but not on the scale that was originally envisioned by some. Site-specific, sustainable harvests are likely to be made in areas where cereal residues are a part of a mixed (or multiple) feedstock strategy for biomass processing plants.

6.5 Key Outputs

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Machado, S. 2011. “Soil Organic Carbon Dynamics in the Pendleton Long-Term Experiments: Implications for Biofuel Production in Pacific Northwest.” *Agronomy Journal* 103 (1): 253–60. doi:10.2134/agronj2010.0205s.

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Wiersma, J., J. Dai, R. Karow, M. Ottman, B. Brown, J. Ransom, J. Edwards, M. Flowers, B. Bean, G. Morgan, B. Bruening, and C. Lee. 2016. "Harvest Index and Straw Yield of Five Classes of Wheat." *Biomass and Bioenergy* 85: 223–7. doi:10.1016/j.biombioe.2015.12.023.

7. Conservation Reserve Program Land (Primarily Mixed Grasses)

7.1 Description/Characteristics

The Conservation Reserve Program (CRP) is a land management program established by the Food Security Act of 1985 that encourages farmers to convert highly erodible farmland or environmentally sensitive lands to relatively low-intensity management vegetation cover (Food Security Act of 1985; Glaser 1986). The main objective of this program is soil and water conservation. Since the lands enrolled in the CRP are already set aside from conventional farm practices, and harvesting biomass from these lands does not require significant land-use change, these lands are potentially a good resource for bioenergy feedstock production if allowed by the program (McLaughlin et al. 2002; Perlack et al. 2005). In addition, many studies demonstrate that removing biomass from CRP lands does not harm or diminish the original environmental benefits intended by the CRP (Burk et al. 1995; Lee et al. 2007a, 2007b; Venuto and Daniel 2010; Chamberlain et al. 2011; Clark et al. 2013). As of April 2015, the total area of CRP enrollment was 24.27 million acres, including 8.2 million acres under contracts that will expire between 2015 and 2019 (USDA-FSA 2015).

Since 2007, over 12 million acres have been converted to row crop production because of recent high commodity prices. Bioenergy feedstock production on CRP land may be an option to maintain the benefits of the CRP (especially if the harvested biomass is a perennial crop) by keeping acreage enrolled while providing landowners additional revenue on top of government rental payment. To help landowners and government officials make decisions, it is necessary to have information on biomass yield potential based on agronomic management practices such as nitrogen fertility and harvest timing management of current CRP land.

7.2 Objectives

The overall goal of this study was to perform long-term, replicated field trials on established CRP land to assess the yield potential and suitability of CRP grassland as a bioenergy feedstock source across logical regions of adaptation.

The specific objectives of this project were to determine maximum biomass yield potential of CRP grassland and species composition changes over time using farm-scale agricultural practices that are standard for each region, including nitrogen fertilization and harvest timing.

To implement farm-scale management practices, the experiment was designed with a minimum of 1.0 acres for an individual plot, to minimize estimation errors caused by weather conditions across the years. Field evaluation was conducted over 6 years, during which a wide range of weather conditions were recorded at each research location. The field study was initiated using already established stands of mixed perennial grasses on CRP lands in 2008 and completed in 2013.

7.3 Methods

Six field research locations were identified based on CRP grassland distribution in the United States in the spring of 2008 (fig. 7-1). The established CRP stands were located at the following sites: Foster County, North Dakota (ND, 47.5°N 99.2°W); Ellis County, Kansas (KS, 38.8°N 99.4°W); Jackson County, Oklahoma (OK, 34.7°N 99.3°W); Chouteau County, Montana (MT, 47.1°N 110°W); Boone County, Missouri (MO, 39°N 92.2°W); and Oconee County, Georgia (GA, 33.8°N 83.4°W).

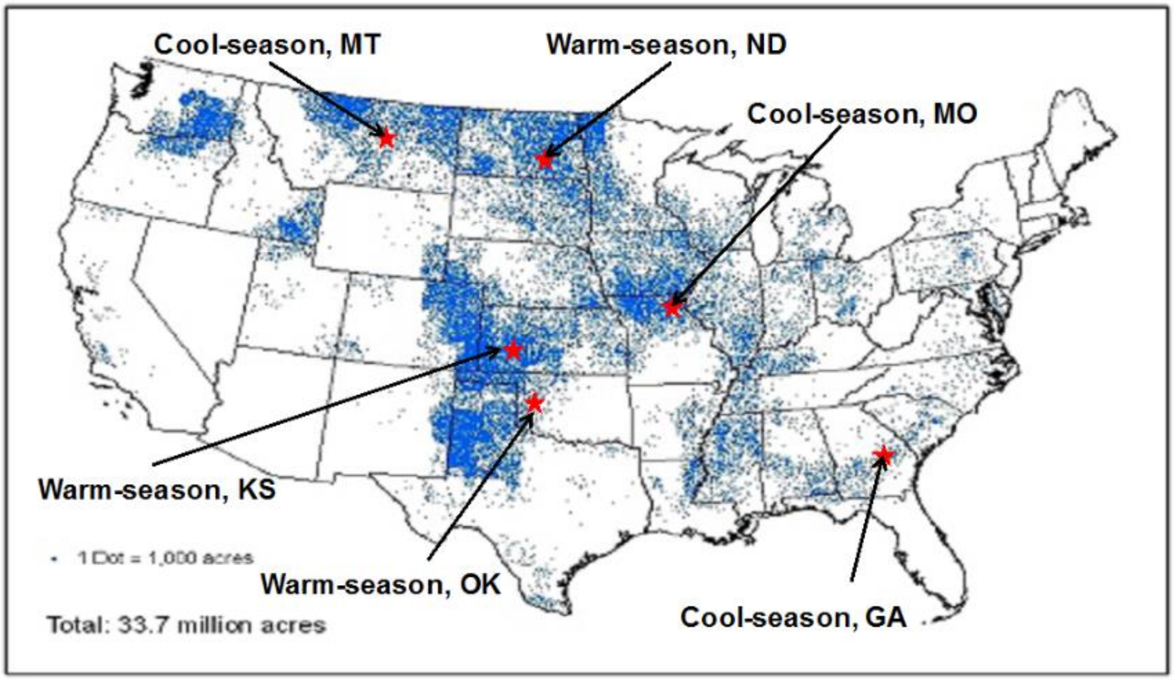

Figure 7-1 | U.S. map of CRP enrollment in 2008 (one dot = 1,000 acres) and of locations (*red stars*) of Sun Grant Regional Feedstock Partnership field trials.

The predominant species varied among the six locations—C_4 grasses (warm-season mixture) at the North Dakota, Kansas, and Oklahoma sites, and C_3 grasses and legume species (cool-season mixture) at the Montana, Missouri, and Georgia sites. Grass mixtures for the region were selected based on the most common mixtures representing regional practices. Nitrogen fertilizer (urea) was annually broadcast with the rates of 0, 50, or 100 lb nitrogen acre^{-1} onto each plot using a farm-scale fertilizer spreader in the spring of each year, and biomass yield and species composition changes were monitored. Biomass yield was determined from a whole-plot harvest with a farm-scale harvester at a cutting height of 4–6 in. For warm-season CRP sites, biomass was annually harvested either at anthesis (peak standing crop, summer) or at the end of the growing season (autumn). For cool-season CRP sites, biomass was annually harvested either at peak standing crop (spring) and/or at the end of the growing season (autumn) depending on location. For the Georgia and Missouri sites, one half of treatments were harvested at both peak standing crop and the end of the growing season to maximize biomass yield. For the Montana site, biomass was harvested either at peak standing crop or at the end of the growing season. These practices varied by site, primarily due to differences in precipitation. For example, sufficient precipitation is received at the Georgia and Missouri sites such that a second harvest in autumn is possible and helps to improve biomass production; the same is not generally true for the Montana, North Dakota, Kansas, and Oklahoma locations, regardless of whether C_3 or C_4 species are used.

All locations were classified as marginal lands, which qualified for CRP enrollment, and all locations had been managed in accordance with CRP regulations, including no nitrogen fertilization and/or aboveground biomass harvest since the start of the contract until the first treatments were imposed in the spring of 2008. Special permission was granted to harvest biomass from these lands for research purposes.

7.4 Results/Outcomes

According to the 2005 *Billion-Ton Study* (Perlack et al.), approximately 25 million acres of CRP land (about 70% of total enrollment in 2007) could be dedicated for feedstock production with the annual yield goal of 2.0 tons acre^{-1} (Perlack et al. 2005). Our long-term field study during 2008–2013 indicates that the biomass yield averaged across locations and years was 1.26 tons acre^{-1} for warm-season mixture CRP land and 2.28 tons acre^{-1} for cool-season mixture CRP land under best management practices. Nitrogen fertilizer was applied at a rate of 100 lb acre^{-1} annually, and the biomass was harvested in the fall (Anderson et al. 2016). Nitrogen fertility was considered the key management practice, and without nitrogen fertilizer application, biomass yields were decreased by 0.65 tons acre^{-1} for warm-season mixture sites and 1.70 tons acre^{-1} for cool-season mixture sites on average. However, biomass yields varied based on year, location, and site-specific dominant species, and all were below the targeted yield of 2.0 tons acre^{-1}. By far, the greatest impacts on seasonal biomass production and changes in vegetation composition were due to location-specific precipitation.

One of the most important findings of the CRP field research as a part of the Partnership is that long-term field-scale research is the first necessary step to determine the potential feedstock production capability of a given feedstock resource. Obviously, the biomass yield in CRP grasslands was lower than expected by the program goal. One reason for the lower biomass yield was lower than normal precipitation levels during the field study period, particularly during the last 3 years of the study. In fact, average yields from CRP field trials across the entire 6-year study were only 47%–58% and 89%–93% of yields observed during the first three years for warm- and cool-season grasses, respectively, primarily because of severe drought during 2011–2013 in the Great Plains region (Lee et al. 2013; Anderson et al. 2016). Annual maximum biomass yields for the warm-season sites in Oklahoma, North Dakota, and Kansas ranged from 0.00–2.70, 1.04–2.12, and 0.18–1.51 tons acre^{-1}, respectively, and for the cool-season sites yields ranged from 1.63–3.20, 1.12–2.20, and 1.00–3.90 tons acre^{-1}, in Missouri, Montana, and Georgia, respectively.

Nitrogen fertility on CRP lands is a key management factor for biomass production and might be more important for sustainable biomass production than on other crop lands because soil quality of CRP land is typically much lower than that of other crop lands. However, the use of nitrogen fertilizer for yield enhancement unambiguously increased the cost of biomass regardless of the harvest timing for all six sites. The breakeven price of biomass at the farmgate ranged from \$63 to \$478 ton^{-1} without CRP rental payment, depending on the rate of nitrogen application, timing of harvesting, and location based on true input costs generated from farm-scale practices (Anderson et al. 2016).

One of the main concerns about using CRP lands for feedstock production, besides losing the original benefits of the CRP, was species composition change, which could negatively impact long-term sustainability of CRP lands. The results demonstrate that CRP land will shift vegetative composition over time based on harvest and fertilization management for biomass feedstocks (Harmoney et al. 2016). Any shift by mismanagement over time to less desirable or less productive species will hinder the ability of CRP land to adequately provide a sustainable or reliable resource for bioenergy feedstock production. Harvest and nitrogen fertility management did not significantly impact species composition of mixtures dominated by cool-season species, other than a decline of legume species under nitrogen fertilization. However, harvest timing management significantly impacted mixtures dominated by warm-season species, with a decline of desirable species by early harvesting (peak standing crop) over time (Harmoney et al. 2016).

Nitrogen fertilization is the key agronomic management factor determining biomass yield on CRP land, but applications of 100 lb nitrogen acre^{-1} are probably not the best economic practice with such low biomass production. Therefore, it is very important to conduct economic analyses based on rental payments, input costs including fertilizer, biomass yield, and price received for biomass (Anderson et al. 2016).

Even though this field research covered a wide range of geographical regions based on CRP land distribution, a longer duration and a greater number of locations based on combinations of species mixtures and precipitation regimes will provide a more accurate estimation of potential biomass feedstock production of CRP land.

The CRP was originally established for soil and water conservation (Glaser 1986), not biomass production. However, CRP land is a potentially important land resource for sustainable biomass feedstock production. Accordingly, in order for CRP lands to be a reliable source of sustainable biofuel feedstock, management considerations must be taken into account that can produce sustainable stands of desirable species and provide ongoing conservation services.

This study evaluated grasslands planted under the CRP as an herbaceous biomass source with potential use as a dedicated bioenergy feedstock. The locations studied were distributed across the country and were evaluated for several years to better understand long-term trends. The results presented here demonstrate, using farm-scale agricultural practices, that CRP land is a potential resource for bioenergy feedstock production if the appropriate management practices are followed under normal precipitation during the growing season. However, CRP lands could increase biomass production through renovating CRP grassland to high-yielding species and/or cultivars recently developed for biomass feedstock production, since current species and cultivars were not necessarily bred for high biomass yield.

7.5 Key Outputs

7.5.1 Peer-Reviewed Manuscripts

Anderson, E. K., E. Aberle, C. Chen, J. Egnolf, K. Harmoney, G. Kakani, R. L. Kallenbach, M. Khanna, W. Wang, and D. K. Lee. 2016. “Impacts of Management Practices on Bioenergy Feedstock Yield and Economic Feasibility on Conservation Reserve Program Grasslands.” *GCB Bioenergy* 8 (6): 1178–90. doi:10.1111/gcbb.12328.

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7.5.2 Outreach Publications

Aberle, E. 2012. “Evaluation of CRP for Cellulosic Biomass Production, 2012.”*North Dakota State University Carrington Research Extension Center Annual Report* 53: 27. http://www.ag.ndsu.edu/CarringtonREC/documents/annual-reports/2012-annual-report.

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7.5.3 Proceedings

Chen, C., J. Heser, T. Porter, and D. K. Lee. 2012. "Nitrogen Application and Harvest Timing Affect Biomass Yield and Composition on CRP Grassland." In *Proceedings of the 2012 Sun Grant National Conference: Science for Biomass Feedstock Production and Utilization*, Vol. 1, Ch. 3.14. New Orleans, LA: Southeastern SunGrant Center, October 2−5. https://ag.tennessee.edu/sungrant/Documents/2012%20National%20Conference/ConferenceProceedings/Volume%201/Vol1final.pdf.

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7.5.4 Presentations

Lee, D. K., E. Aberle, C. Chen, J. Egnolf, K. Harmoney, V. G. Kakani, and R. L. Kallenbach. 2009. "The Regional Biomass Feedstock Partnership: Herbaceous Energy Crops and CRP Land for Biomass Production across Environmental Gradients, CRP Land for Biomass Energy Production in the U.S." Presented at the Sixth Annual World Congress on Industrial Biotechnology and Bioprocessing, Montreal, Canada, July 19–22.

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7.5.5 Workforce Development (Graduate Students, Undergraduate Students, etc.)

This project has funded one master's degree student, one doctoral student, three post-doctoral research associates, and several undergraduate students.

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8. Poplar

8.1 Description and Characteristics

Poplar is known to be one of the most productive tree species adapted to a range of climatic conditions globally (Zamora et al. 2015). Commercial production of poplar in plantations has taken place in many regions of the world where the combination of selected superior genotypes and economic conditions facilitate production of competitively priced feedstock (Stanton et al. 2014; Berguson et al. 2010; Lazarus et al. 2015). Work of the Sun Grant Poplar Team began in 2009 with the purpose of conducting research related to the development of poplar as a woody energy crop nationally. Work underway involves analysis of the yield potential of poplar plantations using selected clones in regional tests throughout the United States as well as development of new parent populations and hybrids to produce a new generation of fast-growing, disease-resistant hybrids adapted to a number of geographic regions of the country. A variety of new yield and genetics field trials were established under the program. In addition to new tests established since 2009, the Sun Grant program allowed the continued measurement of a large preexisting network of field tests. Without these funds, many of these legacy sites would likely have been abandoned with no measurements taken. As a result, prior investment by universities and industry across the country, combined with the DOE/Sun Grant funds, made possible an unprecedented program with federal funds adding needed research infrastructure to a foundation of existing sites. The resulting program has produced significant progress in nationally-coordinated poplar research related to advanced breeding, field testing, yield analysis, and evaluation of wood characteristics of poplar.

8.2 Objectives

The field testing program contains a range of yield studies, clone tests, and larger scale family field trials underway at a variety of locations ranging from the Pacific Northwest, upper Midwest, alluvial Mid-South, and Southeastern regions. Figure 8-1 shows the location of poplar study sites across the United States that were included in the Poplar Team’s field testing network.

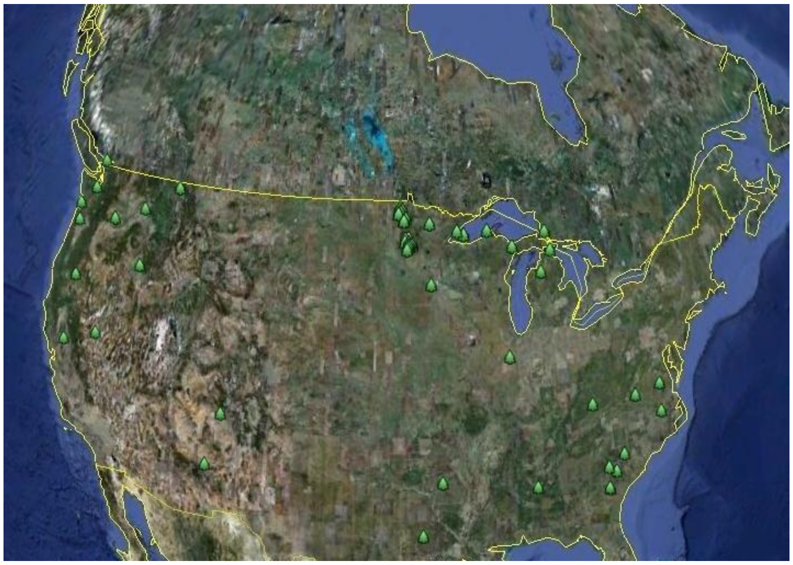

Figure 8-1 | Location of poplar field test included in the Sun Grant Regional Feedstock Partnership trial network.

For clarification, the family field trial sites are located in Minnesota and are part of the breeding and field testing program with a specific purpose to estimate variance components at the family, clone-within-family and within-clone levels thus allowing estimation of additive and non-additive genetic effects. Estimation of these variance components provide important insight into the design of future breeding programs and estimation of gains in biomass yield that can be expected in each generation of breeding and selection. To our knowledge, no trials of this type and scale have been done on poplar prior to the Sun Grant program. These tests are the first step in the development of new clones with many clones planted, typically, 600 to 900 clones. While family field tests contain many clones within families, clone tests typically include fewer clones that have been selected from a larger population with these tests containing more replicates of each clone (four to six single-tree replicates). Clone tests are planted at multiple sites within a region with the primary purpose to evaluate stability in growth across sites. Once a reduced set of superior clones has been selected for growth rate and disease from clone tests, yield tests are planted to evaluate growth of single clones under conditions similar to commercial-scale planting. Clones are planted in three replicated blocks of sufficient size to eliminate edge-effects and estimate biomass yield in absolute terms (e.g., tons acre^{-1} yr^{-1}) as opposed to relative terms, as is the case in family field tests and clone tests. Data from a combination of yield block tests and commercial plantations provided the foundation for the national maps of expected biomass yield developed by the Oregon State University Parameter-Elevation Relationships on Independent Slopes Model (PRISM) group. Tables 8-1 and 8-2 show the current Sun Grant field tests underway by state and trial type.

Table 8-1 | Sun Grant Populus Field Trials by Establishment Year, State, Study Design with Family and Clone Composition, Number of Sites, and Study Size

Year	State	Study	Source	Families	Clones	Sites	Acres
1999	MN	Family Field Trial	1996 CP[a]	21	563	1	1.6
1999	MN	Family Field Trial	1996 OP[b] *P. deltoides*	78	1170	1	2.7
2000	MN	Family Field Trial	1996 CP & 1997 CP	38	684	1	2.0
2000	MN	Family Field Trial	1997 OP *P. deltoides*	50	750	1	1.7
2001	MN	Family Field Trial	1998 CP	69	1725	1	13.1
2002	MN	Family Field Trial	1999 CP	33	899	1	7.4
2003	MN	Family Field Trial	1999 CP	27	907	1	7.4
2004	MN	Family Field Trial	2002 CP	35	785	2	10.8
2005	MN	Family Field Trial	2003 CP	33	511	2	16.4
2006	MN	Clone Trial			70	2	2.0
2006	MN	Yield Blocks			22	2	16.3
2007	MN	Family Trial	2003 CP & 2004 CP	40	672	2	10.2
2007	MN	Clone Trial			70	2	2.0
2007	MN	Yield Blocks			12	2	8.1
2008	MN	Family Field Trial	2005 CP & 2006 CP	45	400	1	4.6
2008	MN	Clone Trial			70	6	6.0
2009	MN	Clone Trial			70	3	3.0

Year	State	Study	Source	Families	Clones	Sites	Acres
2009	MN	Clone Trial	2005 OP *P. nigra*	10	46	3	2.1
2009	MN	Yield Blocks			10	3	7.5
2010	MN	Family Field Trial	2007 CP	30	400	1	4.6
2010	MN	Clone Trial			70	2	2.0
2010	MN	Yield Blocks			10	3	5.1
2011	MN	Clone Trial			98	2	2.6
2011	MN	Yield Blocks			12	2	4.0
2008	MI	Yield Trial			7	1	
2010–2012	MI	Yield Test			16	5	
2010	GA	Yield Block			7	1	2.0
2003	GA	Clone Trial			120	2	2.6
2010	GA	Yield Block			2	1	0.6
2008	SC	Clone Trial			243	1	1.54
2011	SC	Clone Trial			84	1	1.0
2009	SC	Clone Trial			162	1	2.1
2013	SC	Clone Trial	*P. nigra*		690	1	2.8
2009	AL	Clone Trial			162	1	2.1
2009	AL	Clone Trial			124	1	0.9
2010	NC	Clone Trial			87	1	0.5
2010	NC	Yield Block			9	1	2.1
2010	NC	Yield Block			10	1	0.22
2013	TN	Clone Trial	*P. nigra*		670	1	1.5
2013	VA	Clone Trial	*P. nigra*		690	1	1.4
Totals					13,109	68	164.56

[a] CP designates a controlled cross or controlled pollination.

[b] OP designates an open pollination or plant collected from the wild.

Table 8-2 shows sites included in Sun Grant tests under management by GreenWood Resources. These trials include a range of studies, including Bioenergy Trials, which are single-tree plots replicated 3 or 4 times containing 80 to 89 clones; Consolidated Clone Trials, which contain a complement of clones from the Sun Grant cooperators with 20 clones each of four sources in a single tree design with six replicates; Stage I Trials, which are tests of multiple seedlings with no replication (initial observation of adaptability); Stage II trials, which are clone trials containing eight, single-tree replicate plots of many clones; and Stage III tests, which are block plantings embedded in operational acreage typically having four replications of 8 to 20 clones depending on year planted. Also, nursery tests and orchards are comprised of collections of a range of genotypes for purposes of propagation (nurseries) or further breeding (orchards).

Table 8-2 | GreenWood Resources—Sun Grant Populus Field Trials by Establishment Year, Study Name, Location, and Status

Year	Name	Location	Families	Clones	Status
2009	SG Bioenergy Trial	Boardman, Oregon	NA	89	Active
2010	Consolidated Clone Trial	Boardman, Oregon	NA	80	Complete
2011	Consolidated Clone Trial	Boardman, Oregon	NA	80	Complete
2011	Stage I Trial	Boardman, Oregon	46	2.275	Complete
2012	Stage I Trial	Boardman, Oregon	46	3.045	Active
2012	Stage II Trial	Boardman, Oregon			Active
2013	Orchard	Boardman, Oregon	NA	568	Active
2013	Stage I (*P. deltoides*) Trial	Boardman, Oregon	37	786	Active
2013	Stage I (*P. nigra*) Trial	Boardman, Oregon	12	778	Active
2014	Stage I (*P. tricho., P. nigra*)	Boardman, Oregon	28	558	Active
2014	Stage II Trial	Boardman, Oregon	37	458	Active
2015	Stage I (*P. deltoides*) Trial	Boardman, Oregon	35	753	Active
2011	Stage III Trial	Boardman, Oregon	NA	7	Active
2012	Stage III Trial	Boardman, Oregon	NA	16	Active
2013	Stage III Trial	Boardman, Oregon	NA	11	Active
2014	Stage III Trial	Boardman, Oregon	35	41	Active
2015	Stage III Trial	Boardman, Oregon	26	54	Active
2009	SunGrant Bioenergy Trial	Westport, Oregon	NA	168	Active
2010	Stage II Trial (*P. maximowiczii*)	Westport, Oregon	30	183	Complete
2010	Consolidated Clone Trial	Westport, Oregon	NA	38	Complete
2011	Consolidated Clone Trial	Westport, Oregon	NA	82	Complete
2007	LCTF Stage III Trial	Clatskanie, Oregon	5	9	Complete
2008	LCTF Stage III Trial	Clatskanie, Oregon	6	6	Complete
2009	LCTF Stage III Trial	Clatskanie, Oregon	8	9	Complete

Year	Name	Location	Families	Clones	Status
2011	LCTF Stage III Trial	Clatskanie, Oregon	7	7	Active
2012	LCTF Stage III Trial	Clatskanie, Oregon	7	7	Active
2013	LCTF Stage III Trial	Clatskanie, Oregon	8	6	Active
2014	LCTF Stage III Trial	Clatskanie, Oregon	17	19	Active
2015	LCTF Stage III Trial	Clatskanie, Oregon	15	38	Active
2014	2014 Clonal Screening Trial	Fitler, Mississippi	184	1,223	Active

8.2.1 Duration

The field tests shown in the above table were measured annually over a range from 5 to 6 years depending on establishment date. Trials that were established prior to 2009 included 6 years of measurement. Sites established after 2009 were measured annually since establishment.

8.3 Methods

The extreme genetic diversity and the ability to generate fertile offspring from interspecific crosses within and among *Populus deltoides*, *P. nigra*, *P. trichocarpa,* and *P. maximowiczii* present great opportunity to capitalize on this variation to improve yield and disease resistance of poplar as an energy crop. However, no method currently exists to estimate *a priori* performance of clones in a given region and circumvent the process of planting regional field trials to observe growth rate and disease resistance under field conditions over time. While alternate methods are being explored, disease resistance of poplars can change through time as pathogen abundance and virulence changes (Dunnell 2016). As a result, clone tests are a necessary part of research to identify the subset of clones from a larger collection that could be considered for commercial release in operational biomass production, as well as the next generation of parents to be used in further breeding efforts. Also, identification of the best genotypes suited to a region is critical to deciding the subset of clones to be used in more intensive research (such as enhanced yield analysis under various management scenarios using different stand spacing) or in coppice management (Miller and Bender 2012). An additional consideration is that the phenotype of growth rate and disease resistance is not immediately evident, and growth ranking among clones can change significantly over time. In light of this reality, clone trials must be done in the target regions and be maintained over a sufficient time period to identify those clones that are most promising for commercial production. Based on our experience, clone tests should be done for a least half of the final harvest rotation length to minimize risk of significant changes in rank through time. Further, clone performance at one site within a region may or may not be stable across other sites within that region (due to soil and/or climatic effects, among others, for instance). This significant “genotype-by-environment interaction” and changes in clone ranking over time necessitate intensive testing across multiple sites within a region once a subset of superior material has been identified.

It should be noted that a large pool of clones suited to a region can only be derived through a breeding program. Initially, clonal material can be selected from wild populations, but further progress can only be made through breeding. Collection of populations from the wild is a first step in the process but cannot be the final step. Breeding both within and among candidate species must be done to improve yield, disease resistance, and other characteristics such as rooting ability from hardwood cutting, wood characteristics, and tree form. The Sun Grant Poplar Team has carried out the process of breeding simultaneously with clone testing to provide a source of new plant material for continued yield improvement. The phases of genetic improvement and field testing will be discussed in greater detail in their respective sections.

Cooperative Clone Tests were one avenue of clone testing pursued by the Poplar Team. These tests were planted at various locations in 2009 and 2010. Because research partners had access to or owned unique collections of poplar that warranted further testing, we were in a unique position to begin the process of interregional exchanges of clones with selections from four distinct collections. Twenty clones from each of four collections for a total of 80 clones were planted at four locations to evaluate clone growth rate and adaptability across a wide geographic range. The design of these trials is three replications of two-tree plots. Tests were not fertilized or irrigated in the Midwest and Mid-South but were irrigated in the Pacific Northwest and irrigated during the dry periods only in the South.

Genetic improvement research involves several phases of research. These include (1) clone testing of potential pure-species parental stock typically collected from wild populations, (2) inter- and intra-specific breeding of selected parents to produce many progeny, among which improved genetic material may eventually be found, and (3) field testing of progeny resulting from the breeding program to understand fundamental genetic mechanisms and identify the next set of promising clones for inclusion in a new round of breeding and field clone tests. We make the distinction between (1) clone tests of pure-species collections with the primary aim of identifying new parents for breeding and (2) clone tests of a subset of hybrids and pure-species clones with the near-term goal of identifying new material for commercial development.

A debate has existed within the poplar community regarding the underlying genetic mechanisms affecting growth rate and yield of an individual clone. Answers to these questions are important to both researchers and funding agencies as genetic effects have direct bearing on the breeding strategy and the expected rate of improvement in yield that can be expected with each generation. Because poplar can be effectively deployed as clones and not seedlings, we have the unique ability to explore research questions regarding the underlying genetic effects in operation within this species group. Having access to complete populations resulting from a breeding program provides unique advantages for research in that we are able to plant populations of specific genetic composition in long-term field studies of genetic variance within poplar at two levels, family and clone.

Specifically, the aim of this research is to estimate the contribution of families (additive variance component) and clones (non-additive variance component). The practical issue (as it relates to the breeding program) is that if the genetic system is dominated by non-additive effects with very little additive effects, then little justification exists for a structured breeding program to test parental performance prior to using selected parents in breeding. In other words, if ultimate field performance depends entirely on the specific genetic combination residing in a specific clone, parental makeup has little influence, and all clones resulting from the breeding program must be maintained in order to evaluate the population and identify potential new commercial clones. On the other hand, if additive effects are known to be in operation, then the contribution of the parents does indeed “carry over” to the specific family, and all full-sib members of that family share a common trait; again, in our case, the primary trait of interest is growth rate or yield.

The ultimate goal of the Partnership was to increase yield and decrease commercial risk associated with biomass feedstock production. In the case of poplar, once a subset of promising clones is identified in a region, the logical next step is propagation in greater numbers and planting of tests designed to estimate yield potential in closed-canopy, pure-clone blocks more closely resembling larger commercial plantations. This phase of testing requires planting replicated blocks of clones to measure absolute yield in terms of tons per unit area, as opposed to relative growth rates measured in clone tests. For the sake of clarity, yield data reported here reflect the mean annual incremental production at the point of maximum growth, including all years of plantation management. During the early stages of plantation development, production is quite low compared to future production after crown development has been achieved. This is particularly important when comparing annual yields of perennially-harvested crops (such as switchgrass or miscanthus) to woody crops (including poplar and willow).

As mentioned in the introduction, the Poplar Team had access to a variety of sites that pre-existed the formation of the Partnership. The plantation acreage located in the alluvial Mid-Southeast is one such case. Large acreages of commercial plantations were planted as a result of the Mead Westvaco operation surrounding Wycliffe, Kentucky. However, very little data existed that allowed estimates of biomass production on these sites. Also, many of these sites ranged in age from 5 to 11 years with an average age of 8 years and, as such, provided a unique opportunity to measure yields on plantations that are close to achieving maximum production.

8.4 Results/Outcomes

Results of analyses of the four Cooperative Clone Tests show that species composition and source of material are significant factors influencing clone growth and disease susceptibility in all regions. As expected, clones of northern origin planted at southerly locations, while surviving, showed reduced growth compared to those clones derived from collections native to the respective region. This is a photoperiod response inherent to northerly derived material whereby trees from this region cease active growth too early in southern environments. Conversely, clones of southern origin did not survive the cold winters of Minnesota. However, statistically significant correlations between clone ranks in Minnesota and Oregon indicate that clone exchanges and testing of material between these locations may have merit. Overall, clone performance was quite variable with volume (interchangeably, biomass), with the ten fastest-growing clones typically being 1.3 to 1.5 times the test mean. Also, analysis of branch and stem canker prevalence shows that, when planted in the humid southerly locations, some hybrid clones containing *P. trichocarpa* may exhibit increased susceptibility to *Septoria* canker. Field observations suggest that trees start developing cankers as early as the second growing season. While there are exceptions, as a general rule it appears that the native *P. deltoides,* and possibly *P. nigra,* may be the species of primary interest in the southern regions of the United States. This information has helped shape the field testing program and provided the impetus to accelerate testing of pure-species *P. nigra* in the alluvial South and Southeast. Results of these tests have helped identify those clones to be included in further yield tests in the respective regions, which aim to answer questions related to yield potential in each region using superior genetic material.

In addition to the Cooperative Clone Tests, a number of tests were planted that contained only clones collected from the wild that were derived from more local sources. These tests typically included a greater number of regionally derived clones in a replicated design, typically including six replications of each clone in single-tree plots in a randomized complete block design. These tests were planted at sites in the Southeast, Midwest, and the Pacific Northwest. These tests typically included clones that had not undergone extensive testing in the region previously. Pooled results of tests in the Southeast showed a gain of up to 35% in tree volume and biomass relative to the standard clone S7C8. In Minnesota and Michigan, clone tests typically showed that mean biomass growth of the 10 best clones in an 80-clone test exceeded the commercial standard, NM6, by an average of 1.5 times at all test locations. The ratio of the best clone at each of five test sites in Minnesota relative to NM6 after five growing seasons was 2.2, indicating significant potential for yield improvement in test sites in the Midwest, Mid-South and Southeastern United States. Across all regions, clone tests of wild accessions demonstrated that testing of new genotypes has significant potential to increase growth rate and genetic diversity of poplar for commercial planting. Results of these trials have identified the subset of clones suitable for more extensive clone and yield testing in the respective regions.

Breeding has been ongoing throughout the duration of the Sun Grant program at locations in Oregon and Minnesota. The legacy of refined parental populations and expertise allowed us to resume breeding under the Sun Grant program. Together, the two breeding programs have produced more than 20,000 new clones, which will serve as the source of new genetic material for future testing in clone trials and yield blocks. These materials are planted in nurseries in Minnesota, Mississippi, and Oregon and are ultimately propagated for field tests. In Minnesota, populations resulting from the breeding program are planted in family field trials containing a large population of genotypes with a threefold aim: (1) to increase biomass growth and disease resistance in the next generation, (2) to enhance genetic diversity and reduce commercial risk, and (3) to provide insight into the underlying genetic mechanisms operating within these populations, to allow for optimal design of the breeding program so that we can accelerate future progress in genetic improvement.

After 5 years of measurement, results of our work across four separate study sites in Minnesota have shown that both additive and non-additive effects are statistically significant. The most important result is that additive effects indicate that yield is indeed a function of parental composition and not random. This indicates that a breeding program employing a pure-species parental testing program with ongoing refinement of the parental populations through intra-specific breeding will ultimately result in continual yield improvement.

Based on our analyses and the relatively early stage of poplar breeding overall, we estimate that gains in biomass growth of roughly 20% to 30% can be expected through each breeding cycle. Future work could include a specific structured program testing parental stock of all potential parental species in each region, with interspecific breeding being done to capture yield gains and desirable commercial characteristics (e.g., rooting ability, tree form). To our knowledge, information of this type is a unique output of the Sun Grant program and is critically important in designing an effective future poplar breeding program.

Due to the interest in hybridization overall and specifically hybridization including *P. nigra* in crosses, we sought collections of *P. nigra* from native regions in Europe. Through the efforts of the programs at GreenWood Resources and University of Minnesota–Duluth, a large collection of *P. nigra* was obtained. Thousands of clones were procured and propagated for distribution to the Poplar Team members. The breadth and magnitude of this collection is unprecedented in North America. Distribution of *P. nigra* collections has continued, with new plantings of this species being maintained at a site in central Minnesota as well as sites in Washington, Mississippi, South Carolina, Tennessee, and Virginia.

It should be emphasized that the Sun Grant Poplar Program has not only produced new knowledge, but has contributed significantly to the physical infrastructure of genetic resources—notably, parental populations that have not existed in North America prior to the program. The significance of these resources cannot be overemphasized. The current network of sites of unique parental populations puts the Sun Grant Poplar Program in a position to conduct structured breeding in a manner that has never been done before. While funding restrictions are a constant reality, these resources are not static in time and may be lost if funding is not maintained. This could represent a setback of 15 years if allowed to lapse, not to mention the lost progress that could be made if the program were to continue.

A total of 26 yield tests are being measured annually under the Sun Grant Poplar Program. Based on these data, total aboveground biomass yield of newer clonal material on moderate sites ranges from 3.5 to 4.5 dry tons acre^{-1} yr^{-1} in the upper Midwest, 8 to 9 tons acre^{-1} yr^{-1}in the Pacific Northwest, and 7 to 8 tons acre^{-1} yr^{-1} in the alluvial South and suitable sites in the upland Southeast region. A total of 1,500 measurements were made on 55 plots to estimate biomass production. Average annual height growth was found to be 9.7 feet, and the mean annual incremental production of the best clones at these sites was approximately 5.5 dry tons acre^{-1} yr^{-1}. This dataset was used in constructing national yield estimates in this region.

Data generated by the Sun Grant Poplar Program were used to produce a dataset of biomass yields across the United States as part of the larger effort to update estimates of yield of dedicated energy crops nationally. Through the leadership of staff at the Oak Ridge National Laboratory and the PRISM Climate Modeling Group at Oregon State, yield data were coupled with soil characteristics and climate to develop relationships between site characteristics and biomass yield. In light of the potential importance of the Southeast and relative lack of publicly available data, we developed reference yield curves for tree height and diameter to allow us to estimate potential biomass productivity in this region. We compared height growth of superior clones in clone tests in the Southeast to estimate yield potential in this region; these data, along with data from other sites and regions, were used to produce the dataset for the national yield mapping effort.

Cooperative research was conducted with the University of Illinois–Champaign/Urbana to evaluate carbon and water fluxes within poplar plantations, contributing to our knowledge of carbon sequestration and sustainability of woody energy crops. The South Central Research and Outreach Center at Waseca, Minnesota, completed work on plantations established and measured by the University of Minnesota–Duluth Natural Resources Research Institute program.

The work of the Partnership has helped develop new methods to evaluate wood chemical constituents and helped delineate the variation in wood density and moisture content, which were important factors affecting commercial conversion facilities.

Information was developed and provided on economic performance for various regions in support of the *Billion-Ton Study* (Perlack et al. 2005), *U.S. Billion-Ton Update* (DOE 2011), and the *2016 Billion-Ton Report* (DOE 2016). Cash flow models were developed using information from commercial operations, particularly from the former Verso Paper operation in Minnesota and the current GreenWood Resources program. This information was put into a cash flow analysis where management inputs are identified and the costs of those practices are delineated on an annual basis through ultimate harvest. Breakeven costs are then calculated using a selected discount rate and the sum of input costs throughout the life of the plantation.

In addition to the fundamental cash flow analysis, work was conducted in Minnesota to estimate the opportunity costs associated with displacing an agricultural crop. While direct replacement of agricultural crops with energy crops was not required, it is nevertheless instructive to consider the reality of displacing energy crops on land that is currently producing agricultural commodities and quantifying the delivered price that one would need to receive in order to pay the farmer or landowner an amount that is cost-competitive with that associated with growing an agricultural crop. Based on estimates of production costs, stand production and harvest and transport economics, DOE's delivered price target range of $70 to $80 per dry ton appears to be achievable on many sites in the Midwest.

The primary barriers to success of commercial implementation include: (1) relatively low and variable energy prices overall, (2) depending on region, potential commercial risk due to lack of intensive yield performance testing of clones on representative sites, (3) disease risk of some genotypes in some regions with incomplete knowledge of disease effects through time, (4) unknown response and need for fertilization in all regions, and (5) lack of knowledge of poplar in longer-term coppice tests under a multiple-harvest scenario (work currently underway).

As noted above, the Poplar Program worked cooperatively with the University of Illinois to estimate water and carbon fluxes in poplar plantations. Also, the genetic material developed as part of Sun Grant activities has attracted worldwide attention; cooperative field trials of this material are underway in Germany, Poland, and Russia, and new tests in Eastern Europe (Lithuania, Ukraine) and Sweden are being established in 2015.

Minnesota—Verso Paper Program. The experience of the commercial venture in Minnesota, while terminated due to a tragic fire at the mill, is instructive in that it points to the need for an established research base to provide knowledge by which to assess the commercial viability of a project. Information on expected yield, management inputs, and genetic material are needed. The prior work done by the DOE-supported projects in Minnesota (University of Minnesota–Duluth) and Wisconsin (USDA Forest Service at Rhinelander Forestry Science Laboratory) was a critical part of setting the stage for a commercial venture in central Minnesota. At the time, clone trials of available material had been in place for 10 years, and many aspects of plantation management, such as clone selection, cutting production, plant spacing, weed control, and disease concerns, had been developed through the research project. This work clearly demonstrated that research done on a relatively small footprint translated well to a larger commercial operation. Also, the experience of the commercial program in central Minnesota pointed to the critical need and opportunity to diversify the genetic base to guard against changes in pathogenic pressure and promote greater adaptation to a range of sites encountered within a region. The fact that only one clone was ultimately used for commercial purposes after a series of clone tests including 70 clones demonstrates the need for the DOE program to continue genetic development and clone testing in anticipation of the eventual emergence of a commercially viable renewable fuels industry. The successful establishment of 25,000 acres of commercial plantations is an example of the critical need for information on genetics, yield, and stand management appropriate for each region.

8.4.1 Recommendations for Future Work (Holes in Current Work or New Directions)

A particularly frustrating and puzzling aspect of poplar clone testing is the lack of site-to-site stability in growth rate within a region. The high degree of "genotype-by-environment interaction" associated with this work requires that a field testing program include many tests replicated within site and across sites within a region in order to have a level of confidence that a particular clone will perform consistently and reduce the risk of plantation failure or underperformance. While there are notable exceptions to this phenomenon, they are a very small subset of clones. Field testing of new clones at multiple sites within a region is necessary to identify those clones capable of adapting to a range of field conditions prevalent throughout the region. It may be possible to approach this problem through testing of parental stock in replicated field tests prior to breeding to determine if it is possible to "breed in" plasticity.

Building on the results of the analysis of family and clone-within-family variance, coupled with the array of flowering collections of superior parents, we are in a unique position to conduct second-generation breeding and secure yield gains available to the program. Research done over the past 5 years in the development of parental collections, understanding of genetic effects, and the demonstrated success of the breeding programs suggests that additional funding could contribute to significant yield improvement and diversification. In order to continue to refine genetics and improve yield, further breeding and field testing of progeny is recommended.

One aspect that the Sun Grant Poplar Program commonly discusses is the lack of information on responses (or lack thereof) of poplar plantations to fertilizer additions, particularly nitrogen fertilization. While it is axiomatic that high growth rates cannot continue without nutrient additions, the lack of response to nitrogen in many environments is puzzling. Our experience in research into nitrogen response has been mixed, with some sites exhibiting statistically significant response to nitrogen and others showing no response. In those cases where fertilization response was noted in Minnesota, the asymptote of the response curve occurred at relatively low rates (80 lb acre^{-1} of elemental nitrogen) with no additional benefit of annual fertilization over biennial fertilization. There is a need to link site type, site management history, and nitrogen status (possibly using chlorophyll meters calibrated for poplars) to identify those conditions where fertilization may prove to be cost effective. To date, that understanding is unclear and is a subject for more research. Related to this, life-cycle analyses are heavily influenced by energy inputs, and nitrogen fertilization represents a potentially high energy input into these analyses. Thus, nutrient response and the need for fertilization have an effect on commercial performance and sustainability and energy efficiency.

The effort to construct estimates of expected poplar yield for the regions as part of the national mapping effort highlighted the continued need to first identify promising high-yielding, disease-resistant clones, but then to plant and measure these trials on a wide array of potential site types within each region. This work is viewed as a logical continuation of genetic improvement research to verify yield performance of selected clones in a region. These data are an important part of analyses to estimate production costs and the optimal siting of plantations in a given region.

Questions remain regarding the effect of repeated coppices on long-term production and the variation in suitability of clones in regrowth and maintenance of long-term productivity under a coppice system. While this system has been in place in Europe, and research into coppice systems is underway on both relatively large-scale (GreenWood Resources in the Pacific Northwest) and smaller research plots (University of Minnesota–Duluth Natural Resources Research Institute and Michigan State University), more intensive research on this topic over a longer time period is required before this system can be relied on to produce feedstock on a commercial scale.

8.5 Key Outputs

Key outputs of this study included the following:

- Performed clone tests and selected superior genotypes for each region
- Identified canker-resistant clones in the Southeast and impact of disease prevalence by species
- Produced large quantities (>20,000 clones) of next-generation materials for testing and yield improvement through breeding
- Produced unprecedented infrastructure of parent collections (e.g., imported *P. nigra* collections) to support further breeding through genetic improvement research
- Enhanced understanding of genetic effects and "bang for the buck" in expected yield gain per breeding cycle (at least 20% gain expected per cycle)
- Developed cash flow models and gained better understanding of production economics
- Developed a much more extensive dataset of yield estimates for all regions, with benefits to the national mapping effort
- Supported cooperative research in sustainability and carbon sequestration
- Gained worldwide attention through cooperative research; field tests are underway in Europe using genetic material produced with funding from the Sun Grant Regional Feedstock Partnership.

8.5.1 Presentations and Conference Proceedings

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Berguson, W. E., B. Stanton, and J. Eaton. 2010. "Development of Hybrid Poplar for Commercial Production in the United States: The Pacific Northwest and Minnesota Experience." Presented at Soil and Water Conservation Society – Sustainable Alternative Fuel Feedstock: Opportunities, Challenges and Roadmaps for Six U.S. Regions, September 10, 282–99.

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9. Willow

9.1 Description/Characteristics

Interest in shrub willows (*Salix* spp.) as a perennial energy crop for the production of biomass has developed in Europe and North America over the past few decades because of the multiple environmental and rural development benefits associated with their production and use (Börjesson 1999; Rowe et al. 2008; Volk et al. 2014). Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden, with the first trials in the United States starting in 1986 (Volk et al. 2006). Since the initial trials in upstate New York, yield trials have been conducted in a number of locations in the northeastern and midwestern United States, as well as in several provinces in Canada.

Willow shrubs (*Salix* spp.) have several characteristics that make them an ideal feedstock for biofuels, bioproducts, and bioenergy: high yields that can be sustained for over 25 years in 3- to 4-year rotations, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and chemical composition and energy content similar to other northern hardwood species (Stoof et al. 2015).

The shrub willow cropping system consists of planting genetically improved cultivars in prepared open land where weeds have been controlled. Willow can be grown successfully on marginal agricultural land across the Northeast, Midwest, and parts of the Southeast. Weed control usually involves a combination of chemical and mechanical techniques and should begin in the fall before planting if the field contains perennial weeds, which is often the case with marginal land. Willows are planted as unrooted, dormant hardwood cuttings in the spring as early as the site is accessible at about 6,070 plants acre^{-1} using mechanized planters that are attached to farm tractors and operate at about 2.0 acres hour^{-1}. Following the first year of growth, the willows are typically cut back (coppiced) close to the ground level during the dormant season to force coppice regrowth, which increases the number of stems per stool from 1–2 to 8–13, depending on the genotype (Tharakan et al. 2005). After an additional 3 to 4 years of growth, the stems are mechanically harvested during the dormant season after the willows have dropped their leaves. The coppiced plants sprout again the following spring when they are typically fertilized with about 40 kg nitrogen acre^{-1} of commercial fertilizer or organic sources like manure or biosolids. Further research is underway to refine these recommendations for new willow cultivars across a range of sites. The willows are allowed to grow for another 3- to 4-year rotation before they are harvested again. Projections indicate that the crop can be maintained for seven 3-year rotations before the rows of willow stools begin to expand to the point that they restrict access to harvesting equipment and thus need to be trimmed back with a heavy disk or mower. After 22 years in cultivation, some cultivars will need to be replaced by improved cultivars developed through breeding. This is easily accomplished in one season by killing the existing stools with herbicides after harvesting and then chopping the killed stools with a heavy disk and/or grinding machine, followed by planting the same year or the following year.

The large genetic diversity across the genus *Salix* and the limited domestication efforts to date provide tremendous potential to improve yield and other characteristics, such as insect and disease resistance, and growth form of willow biomass crops. Worldwide there are over 350 species of willow (Kuzovkina et al. 2008; Smart and Cameron 2008), with growth forms ranging from prostrate, dwarf species to trees with heights of greater than 40 m. The species used in woody crop systems are primarily from the subgenus *Vetrix*, which has over 125 species worldwide (Kuzovkina et al. 2008). While these species have many characteristics in common, their growth habits, life history, and resistance to pests and diseases vary, which are important considerations in the successful development of woody crops. The ability for vegetative propagation of most willow genotypes means that once superior individuals are identified, they can be maintained and rapidly multiplied for deployment.

As willow breeding programs in North America and Europe have advanced in the last decade, interspecific hybridization has proven to be a very effective strategy for capturing heterosis for yield in combination with pest and disease resistance, yet we know little about the genomic basis for heterosis in interspecific hybrids.

More specifically, a trend that has emerged that is predominant in *Salix* is the consistent success of crosses between diploid species and tetraploid species in generating triploid progeny that outperform their parents (Serapiglia et al. 2014, 2015). This phenomenon is *not* a major component of breeding in poplar, but it is critical to future cultivar breeding in willow. These triploid genotypes also have reduced reproductive fertility, helping to allay concerns about potential invasiveness. Since USDA's Animal and Plant Health Inspection Service has recently banned the import of *Salix* cuttings into the United States, it is imperative to maintain a strong willow breeding program in North America and to expand existing *Salix* germplasm collections through seed import, if possible.

9.2 Objectives

The objectives of the willow feedstock network are to (1) assess the current and future production potential of willow biomass crops across a wide range of sites in the Northeast and Midwest and (2) use the data from these trials to develop models to estimate yield potential of willow biomass crops across multiple regions.

The project included 18 trials planted between 1993 and 2010 (fig. 9-1 and table 9-1). Two trials with older cultivars were included to provide data on the long-term productivity of shrub willow systems over multiple rotations. An additional eight trials with new cultivars bred in New York, which were established before the start of this project, were included. Finally, eight additional trials were established during this project and included some of the most recently developed cultivars. In addition to the data from these trials, results from seven other trials that were not formally part of this project were included in the data set used to develop regional yield estimates in conjunction with Oregon State University using their PRISM Environmental Model (PRISM-EM). The trials were monitored and measured for most of this project, resulting in data from harvests of one 6th rotation, two 5th rotations, one 4th rotation, two 3rd rotations, eight 2nd rotations, and fifteen 1st rotations. This network of trials is providing essential data on long-term production of willow biomass crops as well as yield information for new cultivars across a range of sites.

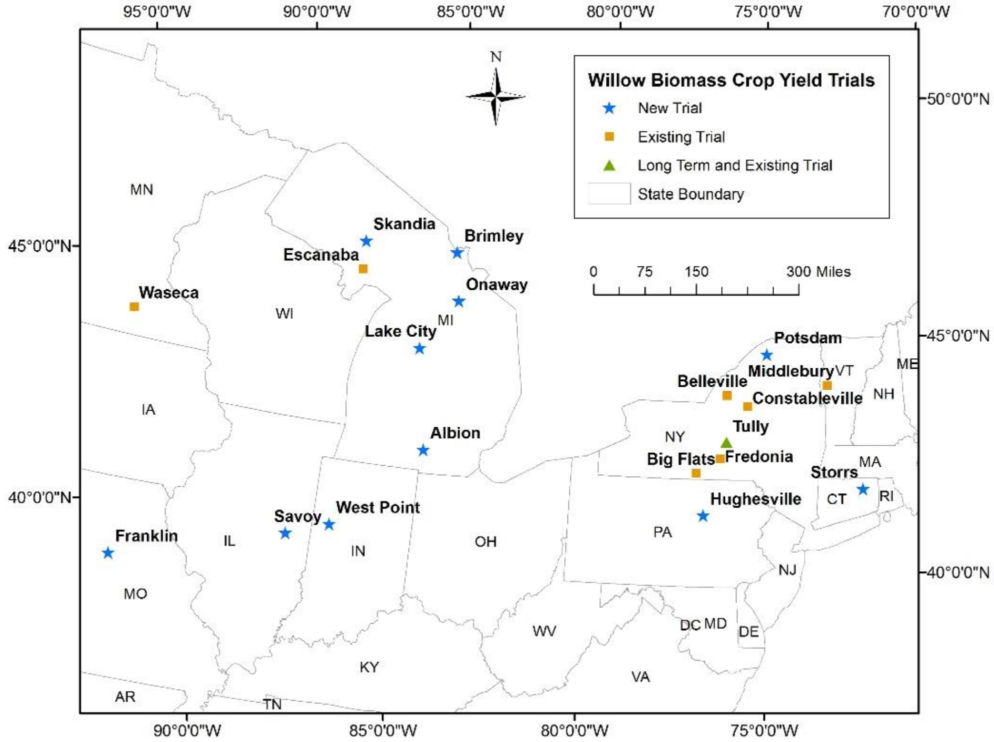

Figure 9-1 | Map showing Sun Grant Regional Feedstock Partnership willow evaluation sites.

Table 9-1 | Existing and New Willow Biomass Crop Yield Trials Included in the Willow Biomass Crop Feedstock Project under the Sun Grant Feedstock Development Program

Trial name	Number of cultivars	Rotations harvested	Soil type[a]	Drainage[b]	Land capacity class[c]	NCCPI[d]
Existing willow biomass trials with older cultivars						
1993 Tully, New York	19	5, 6	Palmyra gravelly loam, 0% to 3% slopes	WD	1	0.48
1997 Tully, New York	32	4, 5	Palmyra gravelly loam, 0% to 3% slopes	WD	1	0.48
Existing willow biomass trials with new cultivars						
2005 Tully, New York	18	2, 3	Palmyra gravelly loam, 0% to 3% slopes	WD	1	0.48
2005 Belleville, New York	18	2, 3	Galway silt loam, 3% to 8% slopes	WD	2	0.39
2006 Constableville, New York	30	1, 2	Empeyville loam, 3% to 8% slopes, stony	MWD	2	0.24
2007 Middlebury, Vermont	30	1, 2	Vergennes clay, 2% to 6% slopes	PD	4	0.49
2006 Waseca, Minnesota	24	1, 2	Nicollet clay loam, 1% to 3% slopes	PD	2	0.80
2008 Big Flats, New York	6	1, 2	Unadilla silt loam, 0% to 3% slopes	WD	1	0.56
2008 Fredonia, New York	28	1, 2	Lordstown channery silt loam, 5% to 15% slopes	WD	3	0.34
2008 Escanaba, Michigan	26	1, 2	Onaway-Ossineke fine sandy loams, moraine, 1% to 6% slopes	MWD	2	0.35
New trials established in 2009						
2009 Sault Ste Marie (Brimley), Michigan	20	1	Rudyard silt loam, 0% to 3% slopes	MWD	2	0.32
2009 Skandia, Michigan	20	1	Munising fine sandy loam, 1% to 12% slopes, dissected	MWD	3	0.17
2009 Potsdam, New York	16	1	Adjidaumo silty clay	PD	4	0.40

Trial name	Number of cultivars	Rotations harvested	Soil type[a]	Drainage[b]	Land capacity class[c]	NCCPI[d]
2009 Storrs, Connecticut	20	1	Woodbridge fine sandy loam, 3% to 8% slopes	WD	2	0.36
New trials established in 2010 and 2011						
2010 Savoy, Illinois	20	1	Catlin silt loam, 2% to 5% slopes	MWD	2	0.78
2010 West Point, Indiana	20	1	Troxel silty clay loam, 0% to 2% slopes	WD	1	0.94
2010 Onaway, Michigan	20	1	Detour flaggy loam, 0% to 3% slopes	SPD	2	0.26
2010 Lake City, Michigan	20	1	Emmet-Montcalm complex, 0% to 6% slopes	WD	2	0.44
2011 Albion, Michigan	20	1	Hillsdale sandy loam, 0% to 6% slopes	WD	3	0.61

[a] USDA National Resources Conservation Service (NRCS) Soil Survey Geographic database soil classification

[b] USDA NRCS soil drainage classes: WD—well drained, MWD—moderately well drained, SPD—somewhat poorly drained, PD—poorly drained

[c] Land Capacity Class rates land on a scale of 1 (few limitations to agriculture) to 8 (unsuitable for agriculture). Under good management, soils from class 1 to 4 are capable of producing common field crops and pasture without reducing the soil's long-term productivity. Soils 5 to 8 have limited value for commercial plant production but may be suitable for use as pasture, range, or forestland, and may also provide opportunities for recreation, wildlife, and water supply.

[d] NCCPI—National Commodity Crop Production Index. NCCPI is a model that interprets soil, landscape, and climate data to reflect soil's inherent capacity to produce dryland (nonirrigated) commodity crops.

9.3 Methods

The project included field trials in six states (Connecticut, Illinois, Michigan, Minnesota, New York, and Vermont). All trials in this project were smaller-scale yield trials with between 4 and 30 genotypes at each site. Individual field plots typically contained three double rows of willow with 10 to 18 plants in each row. Plots were typically 6.9 m in width and 6.0 to 7.9 m long. Most of the trials included four replications of each genotype, but in a few of the older trials, only three replications were available. In the vast majority of cases, the trials were coppiced after the establishment year and then were harvested on 3-year rotations. Site characteristics for the trials varied widely from some better site conditions, particularly at university research stations, to truly marginal conditions at other sites. USDA National Resources Conservation Service (NRCS) land capability class varied from 1 to 4 and the National Commodity Crop Production Index ranged from 0.17 for a site in the Upper Peninsula of Michigan (Skandia) to 0.98 at the site in Illinois (Savoy). Based on NRCS soils data, drainage conditions at the sites varied from moderately well drained to poorly drained.

Overall, 94 different willow genotypes were included in these trials, representing more than 10 different diversity groups (a diversity group represents a willow species or particular hybrid). Trials planted before 2005 included older genotypes that were either acquired from the University of Toronto or were collected from the wild in the northeastern United States. Following 2005, the majority of genotypes in trials were based on breeding work that had been done at the State University of New York College of Environmental Science and Forestry. Only one cultivar is present in all 18 trials: *Salix* × *dasyclados* 'SV1'. Three other cultivars are present in 17 of the 18 trials (*S. eriocephala* 'S25,' *S. miyabeana* 'SX61,' and 'SX64'). Eight other cultivars are present in 14–16 trials in the network.

9.4 Results/Outcomes

First-rotation yields were generated for a wide variety of cultivars across sites with a range of conditions across a broad geographical range. For trials planted after 2005, the yield of the top-producing, newer cultivars at the end of the first rotation ranged from 1.6 (Potsdam, New York) to 7.1 dry tons acre^{-1} (Storrs, Connecticut). The mean across the sites was 4.7 ± 0.5 dry tons acre^{-1} yr^{-1}. The current recommendation for large-scale plantings of willow biomass crops is that multiple cultivars should be planted at each site to minimize risk. Therefore, reporting yields of the top three or top five cultivars at each site is more representative. The yield of the top three cultivars across the sites ranged from 1.3 (Potsdam, New York) to 6.3 (at Middlebury, Vermont, and Storrs, Connecticut) dry tons acre^{-1} yr^{-1}. The mean across the sites was 4.3 ± 0.4 dry tons acre^{-1} yr^{-1}. The yield of the top five cultivars across the sites ranged from 1.2 (Potsdam, New York) to 6.2 (Middlebury, Vermont) dry tons acre^{-1} yr^{-1} with a mean across all the sites of 4.1 ± 0.4 dry tons acre^{-1} yr^{-1}.

Willow biomass crops are cultivated in a perennial system that is typically harvested multiple times on 3- or 4-year rotation cycles, and they have projected lifespans of over 25 years. However, data on the long-term production potential of willow biomass crops are very limited. The trials in this project have provided valuable results on the production of willow over multiple rotations. One trial planted in 1993 in Tully, New York, was maintained as part of this network and has now been harvested six times, providing the longest continuous set of yield data from a shrub willow trial in North America. While many of the cultivars planted in this trial have been replaced with more productive cultivars, one cultivar ('SV1') has been used for many years in both trials and large scale plantings of willow and is present in all the trials in this project. Over six rotations, the yield of 'SV1' ranged from 4.0 dry tons acre^{-1} yr^{-1} in the first rotation to 6.8 tons acre^{-1} yr^{-1} in the fourth rotation. In the sixth rotation, the yield decreased to 5.0 dry tons acre^{-1} yr^{-1} but was still 26% greater than the first-rotation yield. Across all six rotations, the average annual yield was 5.5 dry tons acre^{-1} yr^{-1}. A 12-year-old trial in Michigan compared poplar and willow hybrids under multiple 3-year harvest cycles and determined that while poplar initially thrived, it could not withstand repeated harvests as well as willow. These long-term data begin to provide verification that willow can be productive over multiple rotations and provide a basis for modeling these systems over 25 or more years.

This network of field trials with the large number of cultivars has provided essential information on potential yield increases associated with breeding and selection efforts. Yield increases associated with new cultivars have typically ranged from 15–25%, with some variation across sites. The broad range of sites included in this project has provided a valuable basis for understanding factors that influence willow production and genotype-by-environment interactions (Serapiglia et al. 2013). The factors that have greatest impact on yield can include temperature during the growing season, growing degree days, and regional pest pressure. Despite the heavy influence of site conditions on overall yield, some important patterns have emerged, including evidence that triploid hybrids, such as *Salix viminalis* x *S. miyabeana*, have demonstrated consistently greater yields compared to a range of other taxonomic groups. Since breeding and selection work is still at an early stage for willow, these results suggest that significant gains can still be realized by developing improved cultivars. Data from these sites, along with data from a number of other earlier trials, formed the data base for the development of models to predict the regional yields of willow that are used in the *2016 Billion-Ton Report* (DOE 2016).

Findings from a subset of trials in this network provided important data for a life-cycle analysis that was completed for willow biomass crops. This analysis included all activities beginning with site preparation, harvesting, and delivery of biomass to an end user. This analysis included seven 3-year harvest cycles. Uncertainty analysis was conducted on key variables including yield results from these trials. The GHG emissions from this study were negative for all scenarios (-125 to -48 CO_{2eq} per dry ton) (Caputo et al. 2014) when measurements of belowground biomass were included (Pacaldo et al. 2014). The net energy ratio of biomass delivered to an end user ranged from 18.3 to 43.4, meaning that for every unit of fossil energy invested in the production, harvest, and delivery of willow biomass, there are 18–43 units of stored energy in the willow chips delivered to the end user.

Wood samples collected at first- and second-rotation harvests from a number of these trials have been analyzed for specific gravity and biomass composition via high-resolution thermographic analysis. There are significant differences in biomass composition by genotype, by site, and with significant genotype-by-environment interactions. There are significant positive correlations between yield and cellulose content, with negative correlations between yield and lignin content (Serapiglia et al. 2013; Fabio et al. in prep.). It is known that genotypes and environmental conditions can dramatically affect efficiency of sugar release and potential for conversion to biofuels (Serapiglia et al. 2013; Brereton et al. 2012). Data from these trials will vastly improve our understanding of how environmental factors influence biomass quality and conversion efficiency.

For perennial crops like willow, projection of yields over two or more decades is an important factor that influences key attributes, including the economic viability of these systems. The yield data collected across a range of sites and over multiple rotations as part of this project have provided a solid foundation for improving economic models of this system. Yield data from this network of trials were used to model returns from willow biomass crop systems using a cash flow model developed at the State University of New York College of Environmental Science and Forestry that was updated and improved in 2014 (Buchholz and Volk 2011, 2013; Heavey and Volk 2015). Yield data from this network of trials, and seven other additional trials outside of the network, were used to develop yield models using PRISM-EM across multiple regions of the United States. These yield results, along with production, management, and harvesting costs from EcoWillow 2.0, will have been used in POLYSYS for the *2016 Billion-Ton Report* (DOE 2016).

Two important barriers to the large-scale deployment of willow biomass crops include a stable and reliable market and the overall economics of the system. As noted above, there is ongoing expansion of willow biomass production occurring in northern New York, with a commitment from ReEnergy to purchase all the willow biomass that is being grown in the area over an 11-year period. While the price that ReEnergy currently pays for wood chips would make it difficult to justify growing willow from a purely economic point of view, the support for landowners to plant willow biomass crops from the USDA Biomass Crop Assistance makes growing willow an economically viable option. The development of a long-term market and support to reduce upfront costs has made the expansion of willow in northern New York a reality. Another key barrier stems from the misperceptions about willow biomass that already exist among landowners and potential growers, as well as potential end users.

These misperceptions often stem from a common understanding that willow trees are a poor source of firewood. There is a perception that because willow trees tend to grow in wet areas that the wood is wetter and has less energy than other hardwoods. In reality, on a weight basis the moisture and energy content of freshly harvested willow is the same as other hardwoods like beech or maple (Eisenbies et al. 2014). The main difference between willow and other hardwoods is that willow wood density is 25%–35% lower than other hardwoods, which contributes to many of the perceptions about willow as a source of firewood. In terms of yield, willow can produce 5–10 times more tons of biomass per hectare per year than surrounding natural forests, so willow generates more energy on each hectare of land. An additional misperception present among end users is that the particle size distribution of willow biomass is inconsistent and causes problems with feed systems at heating and power plants. This opinion is often based on some bad experiences that occurred years ago during initial trials with willow biomass that was produced using experimental harvesters. The chips from these machines were inconsistent and did cause problems in feed systems. These negative experiences have been widely discussed among plant operators over the years. However, recent developments in harvesting technology, by New Holland for example, have addressed this issue, and the material that is now being delivered to end users has a consistent quality. In the past few years, more than 4,000 Mg of willow biomass has been delivered to end users to generate heat and power. While there was initial skepticism about this fuel source among some plant operators, experience with many loads of willow biomass has shown them that willow is a good quality fuel that is easily mixed with other sources of woody biomass and used in their facilities without any serious problems.

This network of willow yield trials has provided locations where other studies are either underway or have been completed. Without this network of sites and the support to maintain these sites over an extended period of time, these studies would not have been possible. In New York, these related studies include assessments of belowground biomass, changes in soil carbon over time, characterizations of willow so the Revised

Universal Soil Loss Equation can be used to estimate erosion potential under willow, measurements of sap flow in willow, assessments of fine root dynamics in willow, economic assessments of willow biomass crops, and examinations of genotype-by-environment interactions in willow and variations in willow compositions across a range of sites. In Connecticut, data generated from willow yield trials were used as the basis for developing other projects, including a study called "Agroforestry Riparian Project for Biofuel and Environmental Benefits." This project is now using willow to restore a riparian buffer that impacts a number of ecosystem services including nitrogen and phosphorus runoff, erosion, and sedimentation. Yield trial data formed the foundation for the development of a genotype-by-environment trial of several willow varieties grown on different microsites with different soil attributes. The sites in Michigan were employed to conduct an investigation of the GHG and nitrogen impacts of changing land use from pastureland to short-rotation woody bioenergy crops (Nikièma et al. 2012). Materials from these sites have also been supplied to a variety of other projects seeking to better understand variability of physical and chemical feedstock characteristics.

The network of trials has provided many unique opportunities to highlight willow biomass crops in different communities. Many of the sites were used for field days and extension and education activities, which has been important for the development and expansion of willow biomass crops. Two trials in northern New York in particular (Belleville and Constableville) were essential in the successful application for a USDA Biomass Crop Assistance project area. The trial at Belleville was established on school property, and the Future Farmers of America club at the school engaged in planting and monitoring the willow crop. The site was used for field days and for one of the first public demonstrations of a New Holland forage harvester being used to cut and chip willow stems. Similarly, the yield trial at the USDA NRCS Big Flats Plant Materials Center was highlighted at an annual field day event for several years, with over 100 participants each year. The data from these yield trials provided essential background information that was needed for this application and also provided key locations for landowners and potential growers to see willow biomass crops firsthand. Despite the fact that the sign-up period for this Biomass Crop Assistance project area was limited to about a six-week period, just over 1,170 acres were enrolled. Without the presence of these yield trials, this project would not have been successful, and this commercial expansion of willow biomass crops in the United States would not have been possible.

The data from the network of trials, and especially the data from the trials with newer cultivars, have provided invaluable information for a commercial nursery partner in western New York—Double A Willow—to make decisions about which cultivars to plant in its nursery beds. Currently Double A Willow has about 150 acres of commercial nursery beds and is providing willow planting stock for various projects in the United States, with subcontracts to nurseries in Canada. The data from the yield trials are important for making decisions about what to plant in nursery trials because it takes several years before these nursery beds are productive.

Maintaining a subset of these trials is important for monitoring some of the new cultivars over multiple rotations to provide data on their performance. In addition, findings from some trials with cultivars from breeding efforts that have been conducted over the past few years are beneficial for continuing to improve the genetic material that is available for future deployment. As willow crops are deployed on a commercial scale, it becomes especially valuable to conduct focused monitoring across large fields. This would provide valuable data on the economics, production, and sustainability of willow biomass crops at a much larger scale and provide an opportunity to optimize various parts of the system.

At the beginning of this project, willow biomass crops were limited to a small network of yield trials and a few scattered larger-scale demonstration plantings. This project has supported an important expansion of the network of yield trials and has enabled researchers in a number of regions to leverage this support for other projects and initiatives. As noted above, this network of trials has provided key data for the expansion of willow biomass production in northern New York. Results from these trials have provided the data needed for the Research Foundation of the State University of New York to patent one willow cultivar in both the United States and Canada.

9.5 Key Outputs

9.5.1 Peer-Reviewed Manuscripts

Caputo, J., S. Balogh, T. A. Volk, L. Johnson, M. Puettman, B. R. Lippke, and E. Oneil. 2013. “Incorporating Uncertainty into a Life-Cycle Analysis (LCA) Model of Short-Rotation Willow Biomass (*Salix* spp.) Crops.” *Bioenergy Research* 7 (1): 48–59. doi:10.1007/s12155-013-9347-y.

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9.5.2 Professional Presentations

Twenty-nine presentations were given at various local, regional, national, and international conferences.

9.5.3 Outreach and Extension Publications

Sixteen extension publications were generated based on the information that was developed during this project: http://www.esf.edu/willow/pubs.htm.

9.5.4 Patents

Data collected as part of this project were used to patent one willow cultivar in the United States and secure plant breeders rights in Europe. Data was also used to file for plant breeders rights in Canada.

1. Fast-growing willow shrub named ‘Preble.’ US20130227752. Issued August 29, 2013.
2. Community plant variety rights for Preble to the Research Foundation of SUNY. Decision N° EU 43064 OF 11 April 2016.

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10. PRISM Environmental Limitation Model (PRISM-ELM)

10.1 Description/Characteristics

PRISM Environmental Limitation Model (PRISM-ELM) is a hybrid statistic/process model that has been used in this project to provide estimates of potential biomass yield for crops with little production history in the United States (Halbleib et al. 2012). The centerpiece of PRISM-ELM is a semi-monthly Food and Agriculture–style water balance simulation, which tracks precipitation input, evapotranspiration, and soil moisture depletion. An estimate of monthly relative yield (0%–100%) is the product of the water stress coefficient and a temperature growth curve. In what is known as a "limiting factor" approach, the final relative yield is the lowest of the modeled yields resulting from the water balance simulation, plant injury curves for summer heat and winter cold, and growth constraints due to soil pH, drainage, and salinity. Climate inputs of temperature and precipitation are provided to PRISM-ELM on a semi-monthly basis using 800-m resolution gridded data from the PRISM climate mapping system.

10.2 Objectives

A major objective of the Sun Grant geographic information system component is to gain an understanding of the spatial distribution of current and potential biofuel/bioenergy crop resources across the country. Biofuel crops have become a point of national focus, with several new crops identified as potential feedstocks. Traditional crops, such as wheat, corn, and sorghum, provide residues that can serve as biofuel feedstocks and have long production histories and rich knowledge bases with regard to physiology, production, and spatial distribution. However, many new crops identified as potential feedstocks, such as switchgrass, miscanthus, energycane, poplar, and willow, have little production history in the United States. It is not surprising, then, that planners tasked with assessing farming, transportation, processing needs, and infrastructure for new crops are asking the basic question: Where can these new crops be raised successfully and how much production can be reasonably expected within a given geographic region?

10.3 Methods

Attempts to estimate the potential spatial distribution and yield of new bioenergy crops have taken two main approaches: (1) empirical models based on field data and (2) application of mechanistic plant growth models (Jager et al. 2010; Nair et al. 2012). Commonly used empirical approaches involve statistical extrapolation of plot/field-level yield data to larger regions and climatic envelope modeling (e.g., Casler et al. 2007; Barney and DiTomaso 2010; Schmer et al. 2009; Araya et al. 2010; Jager et al. 2010; Wullschleger et al. 2010; Tulbure et al. 2011).

Plant growth models attempt to simulate the important physiological processes that affect growth, development, and yield. Most plant growth models simulate photosynthesis, carbon allocation, phenology, biomass production, and root/shoot partitioning. Examples of simulation models include EPIC (Williams et al. 1984; Brown et al. 2000), ALMANAC (Kiniry et al. 2008), and MISCANFOR (Hastings et al. 2009; Miguez et al. 2011).

PRISM-ELM stems from earlier work to estimate the suitability of U.S.-grown perennial grasses in China (Hannaway et al. 2005). It draws from both the statistical-empirical and crop growth modeling approaches, while keeping the modeling system very simple and universal so that assessments can be made quickly and easily over large areas. The basic question we seek to answer is: What is the spatial distribution of the major environmental constraints that limit the production of this crop? The main focus is on general biomass production, rather than a detailed accounting of phenology, flowering, grain development, etc.

The centerpiece of PRISM-ELM is a semi-monthly Food and Agriculture–style water balance simulation (fig. 10-1), which tracks precipitation input, evapotranspiration, and soil moisture depletion (Allen et al. 1998). An estimate of monthly relative yield (0%–100%) is the product of the water stress coefficient and a temperature growth curve. In what is known as a "limiting factor" approach, the final relative yield is the lowest of the modeled yields resulting from the water balance simulation, plant injury curves for summer heat and winter cold, and growth constraints due to soil pH, drainage, and salinity.

Climate inputs of temperature and precipitation are provided to PRISM-ELM on a semi-monthly basis using 800-m resolution gridded daily data from the PRISM climate mapping system. PRISM datasets serve as the USDA's official 30-year "normal" digital climate maps (Daly et al. 2008; PRISM Climate Group 2015).

The water balance model uses PRISM precipitation (*Precip)* to determine total available water (*TAW*) in the soil profile (Halbleib et al. 2012) (fig. 10-1). Available soil water holding capacity (*AWC*) is estimated from the USDA NRCS U.S. General Soil Map Coverage (NRCS 2016), and the depth of the rooting zone (*Droot*) is defined by the user. PRISM monthly average temperature (*Temp*) is used to estimate potential evapotranspiration (*ETo*). Actual evapotranspiration (*ETa*) is a function of *ETo*, a water stress coefficient (*Ks*), the plant's water use efficiency (*Kc,* user-defined), and the root zone moisture depletion (*Dr*), which is the difference between the plant's moisture demand and the soil water supply. *ETa* in a given time interval reduces the next time interval's soil water supply, which is at least partially replenished by precipitation. If *TAW* exceeds *AWC*, the excess moisture (*Em*) is relegated to a deep soil moisture pool, which is available only to woody perennial species. At the end of each time interval, *Ks* is calculated as the difference between *TAW* and *Dr*. Relative yield for that interval is the product of *Ks* and a user-defined temperature growth response function, which defines the relationship between temperature and relative production for that crop.

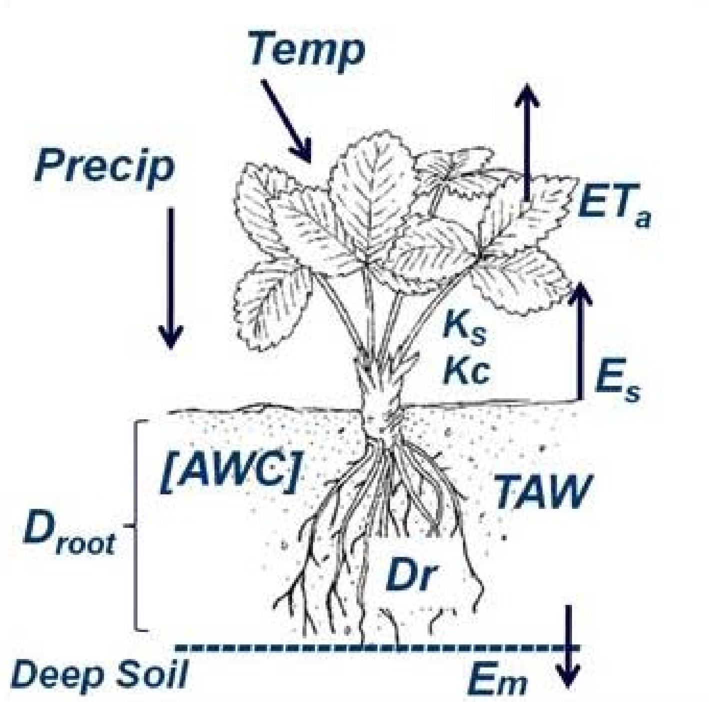
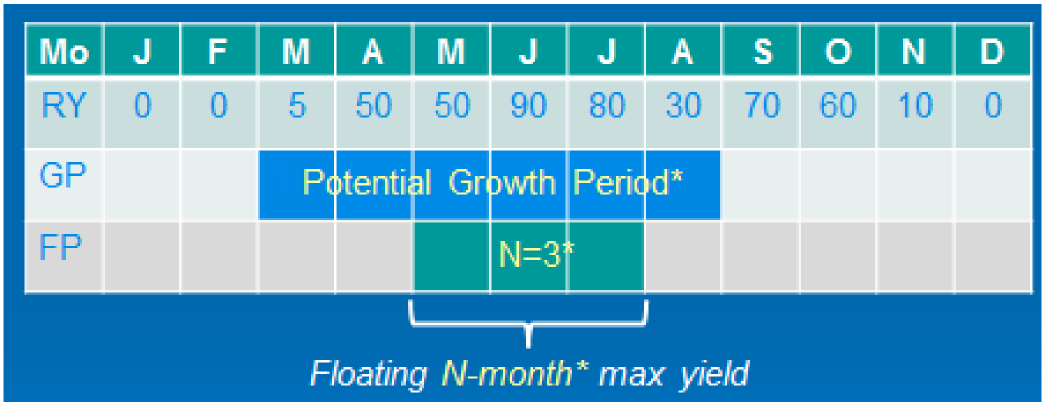


Figure 10-1 | Schematic of the PRISM-ELM semi-monthly water balance model.

The output of the water balance model is a relative yield estimate ranging from 0 to 100 for each month (shown, for example, as RY in fig. 10-2). The user specifies a potential growth period, which is the range of months in which production is likely to occur across the modeling region. In the example in figure 10-2, the potential growth period is March–August. The user also specifies the number of sequential months within the potential growth period over which maximum production is likely to occur. Relative yield values are averaged over these months to obtain a final water balance yield. For example, if the period of significant biomass accumulation is typically 3 months, the user would input N = 3, as shown in figure 10-2. This maximum growth period is allowed to "float," meaning the model will use the 3-month sequence with the highest average relative yield as the final water balance yield, to accommodate varying growing season timing under differing climates.



Mo	J	F	M	A	M	J	J	A	S	O	N	D
RY	0	0	5	50	50	90	80	30	70	60	10	0
GP			Potential Growth Period*									
FP					N=3*							

Floating N-month* max yield

Figure 10-2 | Example of the method used to calculate final water balance yield. RY = relative yield, GP = growth period, FP = floating maximum growth period.

The winter temperature constraint simulates a perennial crop's ability to tolerate and survive winter low temperatures. A two-tailed temperature response function relates the PRISM average January minimum temperature to expected damage or mortality on the cold tail and, if needed, loss of production due to inability to meet winter chilling requirements on the warm tail. The summer temperature constraint simulates a crop's ability to tolerate and survive average summer high temperatures. A single-tailed temperature response function relates the PRISM average July maximum temperature to expected damage or mortality and resultant loss of production.

The soil constraint function for soil pH uses a two-tailed curve that can be broadened or narrowed based on expected plant response to pH, and to accommodate application of amendments such as lime to raise the pH of acidic soils. The soil constraint function for salinity uses a one-tailed curve that represents growth reduction due to increasing soil salinity. The soil constraint function for drainage is based on the seven soil drainage classes as defined by NRCS U.S. General Soil Map Coverage, ranging from very poorly drained to excessively drained. The expected plant response for each drainage class can be set individually, ranging from 0 (full constraint) to 100 (no constraint). Drainage class responses can be modified to account for field tiling to improve poorly drained soils.

The final relative yield is calculated as the *lowest* yield resulting from any of the constraint functions: water balance, winter low temperature, summer high temperature, soil pH, soil drainage, and soil salinity. Model output is in the form of a regularly spaced grid at a native 800-m resolution with an estimate of relative yield from 0 to 100%.

A land use grid can be applied to the relative yield map to mask out land use types that are not classified as agricultural, such as forests, deserts, parks, etc. A useful source of land use coverage is the NASS Cropland Data Layer.

The relative yield map is transformed into an actual yield map by developing statistical relationships between relative and actual yield using available field data. The transformation can be as simple as setting 100% relative yield to a maximum expected biomass yield and scaling the map accordingly, or as complex as using *in situ* yield reports to develop spatially varying relationships across the country.

10.4 Results/Outcomes

As a validation exercise, PRISM-ELM was run using 1981–2010, 30-year average climate data as input, and the resulting gridded and masked relative yield estimates were averaged across each county in the conterminous United States and compared to 10-year (2000–2009) county average grain yields for winter wheat obtained from USDA's Risk Management Agency. The Risk Management Agency requires yield reports from all participants in the federal crop insurance program, resulting in the most comprehensive database of yield information available for the United States. The Risk Management Agency is cooperating with the PRISM-ELM model developers to develop and validate the model as the basis for a decision support tool for estimating crop insurance risk.

A nationwide linear regression analysis was developed relating modeled relative yields against Risk Management Agency average county yields for winter wheat. The overall linear relationship was strong, with an R-squared of 0.77 and y-intercept near zero (fig. 10-3). The PRISM-ELM soil pH and drainage response functions were widened to accommodate relatively high yields achieved by liming acidic soils and tiling of poorly drained soils. Outliers where actual yields exceeded the modeled estimates were found primarily in Idaho and eastern Oregon and Washington. These are areas where counties are very large, and encompass geographic areas with diverse climatic conditions. Farming practices vary from continuous production where precipitation is adequate, to summer fallow to preserve soil moisture where precipitation is limiting. An additional comparison was done between PRISM-ELM relative yields and those reported by NASS. Estimated grain yields were developed using the same nationwide regression approach as with the RMA data. A difference map between PRISM-ELM estimates and NASS reported grain yields shows good agreement (fig. 10-4). Yields were over-predicted in the east-central plains by 5–15 bu acre^{-1}, but the strong east-to-west gradient of decreasing yield with decreasing precipitation across the plains was captured reasonably well. In the eastern United States, where precipitation is generally sufficient, differences may have been caused by local soil conditions, management decisions (e.g., variety selection and fertilizer application), or other economic influences.

Comparisons between PRISM-ELM relative yields and reported grain yields are useful for model validation, but possess uncertainties. PRISM-ELM was driven by 1981–2010 mean climatic conditions, while the yield data represented averages over shorter periods. In addition, grain yield is likely sensitive to different environmental limitations, and their timing and magnitude, than biomass yield. Finally, reported yield data represent a sampling of production outcomes that reflects a myriad of interrelated management decisions and economic forces that can mask the environmental limitations modeled in PRISM-ELM.

The PRISM-ELM relative yield map using Risk Management Agency data was converted to actual biomass yield by applying the nationwide regression function in figure 10-3 to transform relative yield into grain yield, then applying a harvest index, which is the proportion of the crop's biomass allocated to grain, to arrive at an estimate of biomass. Using a harvest index of 0.45 for winter wheat (see chapter 6, Cereal Crop Residues), the biomass map shown in figure 10-5 was produced.

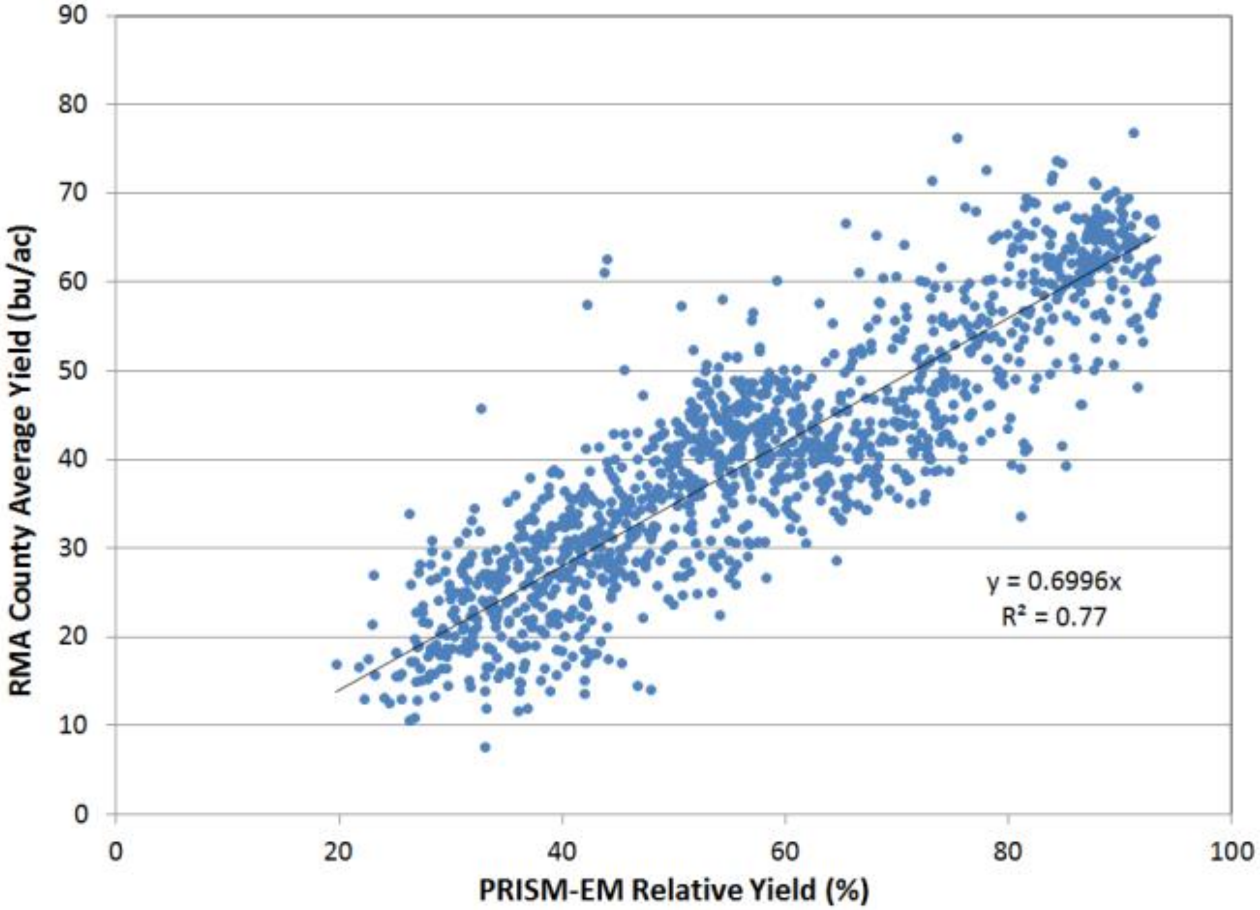


Figure 10-3 | Scatterplot of PRISM-ELM conterminous U.S. relative yield for winter wheat based on 1981–2010 average climate conditions versus the Risk Management Agency county-average winter wheat reported yield over the period 2000–2009.

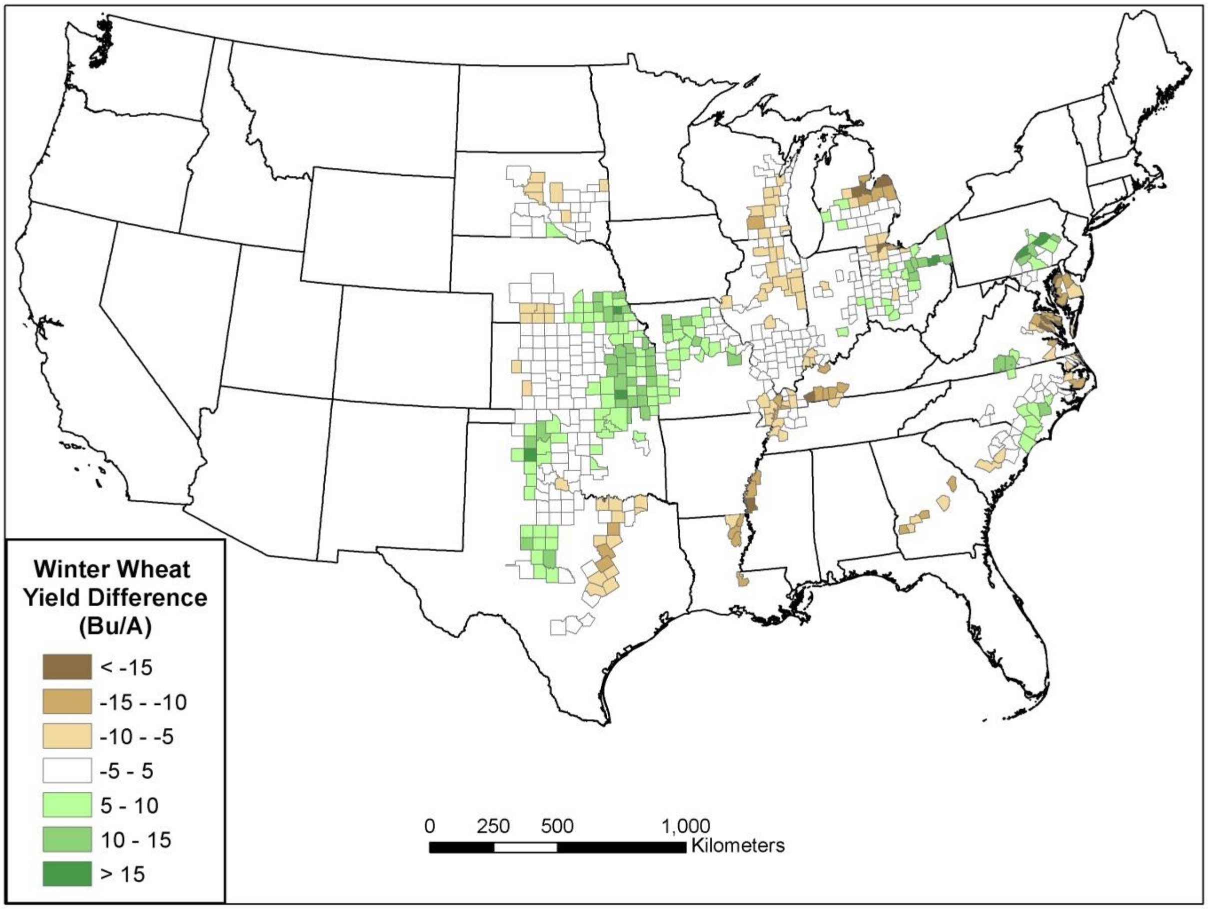


Figure 10-4 | Difference between 2000–2012 average winter wheat yield reported by NASS and PRISM-ELM estimated winter wheat yields, based on 1981–2010 average climate conditions (PRISM-NASS). A national linear regression function between PRISM-ELM relative yield and NASS reported yield was used to transform relative yield into grain yield.

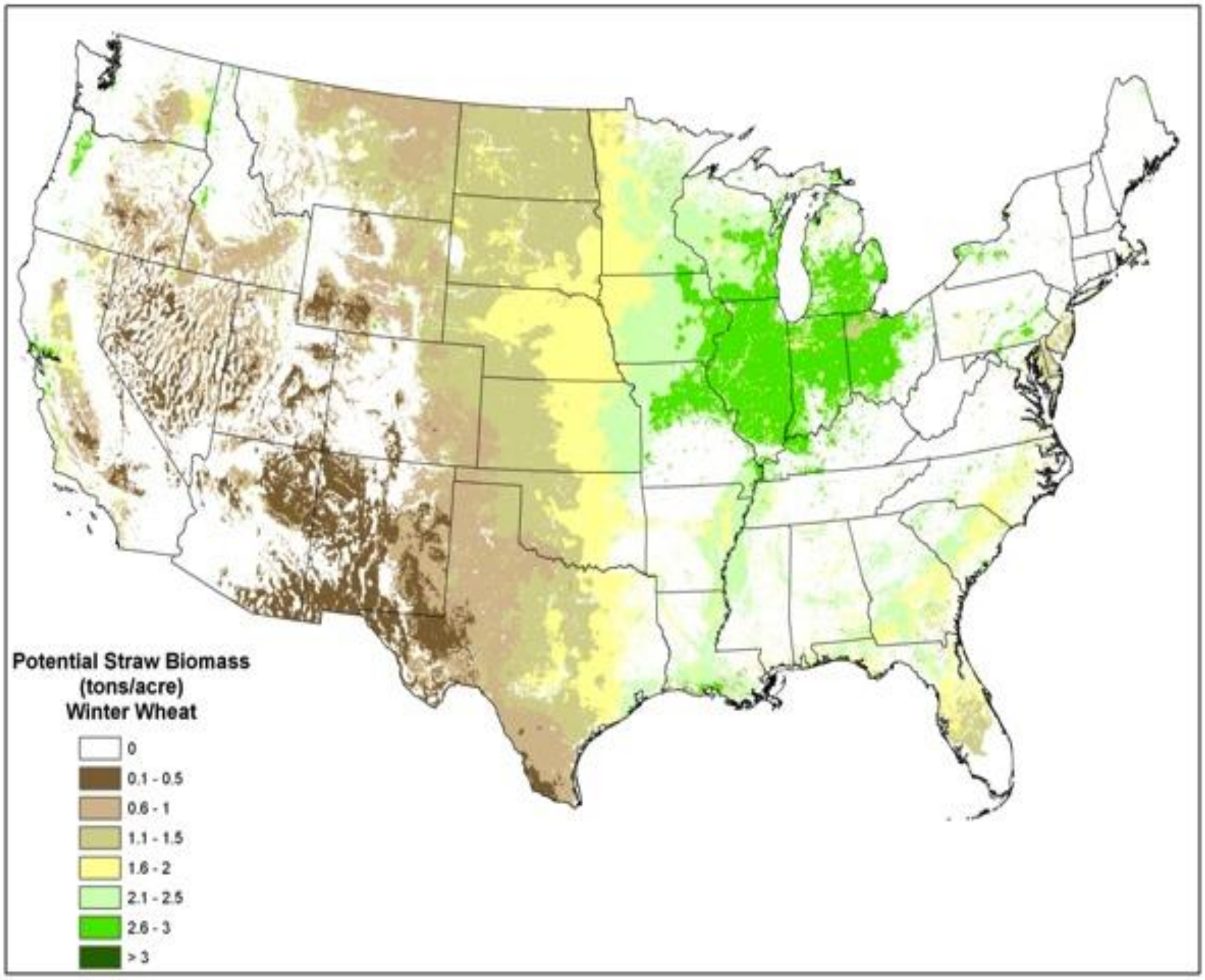


Figure 10-5 | PRISM-ELM modeled winter wheat straw yield, using a linear regression function between relative yield and 2000–2009 average reported yield, and a harvest index of 0.44.

The individual species groups participating in the Partnership provided yield data for most species from several field sites and several consecutive crop years (usually 2009–2014). The modeling team met with each species group in face-to-face meetings. During these meetings, they discussed each data point 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, yield data were supplemented by previously collected data from outside the Partnership. Outcomes from these meetings included draft PRISM-ELM potential biomass maps and scatterplots showing observed versus modeled yields. These were reviewed by each species group, and modifications were made by the modeling team to produce final maps.

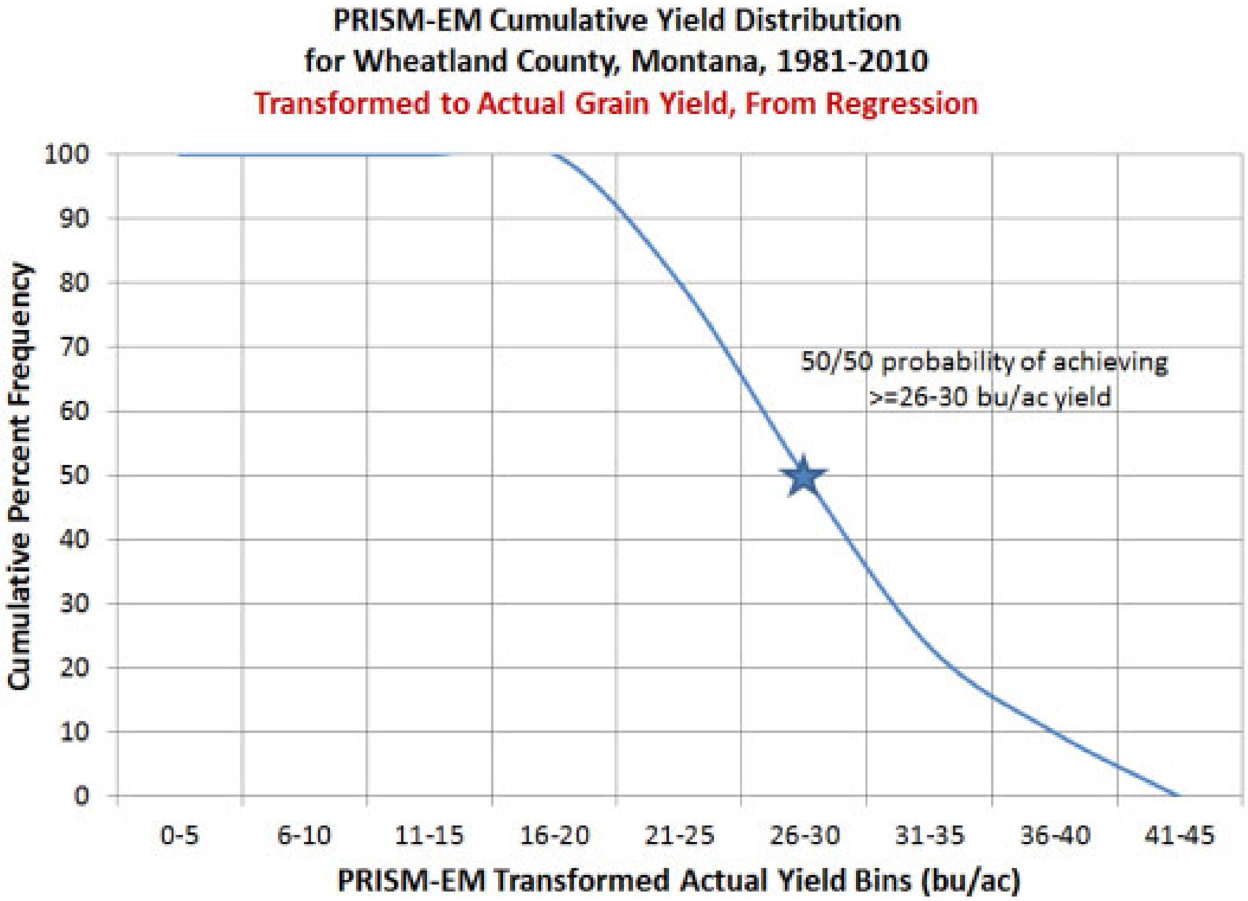


Figure 10-6 | Cumulative yield distribution of PRISM-ELM estimated yields for Wheatland County, Montana, for the years 1981–2010. The probability curve shows the percent chance of attaining a given yield, with the 50th percentile marked with a star.

Maps of 1981–2010 average potential biomass production were produced for energycane, upland and lowland switchgrass, biomass sorghum, CRP grasses, miscanthus, willow, poplar, and southern pine. These maps provide a first look at the distribution of potential biomass production for most nationally important bioenergy feedstock species, using a common modeling and data collection framework, and close collaboration with each species group. These maps are being used as the basis for the economic analysis in the *2016 Billion-Ton Report*.

The potential biomass maps produced by PRISM-ELM represent estimates of average yields expected each year over a 30-year period (1981–2010). The logical next step is to apply the model on a year-by-year basis over those 30 years to obtain a distribution of potential yields that can be used to develop risk assessments. An example shown in figure 10-6 is a cumulative yield distribution function derived from annual PRISM-ELM yields, which estimates the probability of attaining a given winter wheat grain yield in Wheatland County, Montana.

10.5 Key Outputs

10.5.1 Conference Proceedings

Halbleib, M. D., C. Daly, and D. B. Hannaway. 2012. “Nationwide Crop Suitability Modeling of Biomass Feedstocks.” Presented at Sun Grant Initiative 2012 National Conference: Science for Biomass Feedstock Production and Utilization, New Orleans, LA, October 2–5. https://ag.tennessee.edu/sungrant/Documents/2012%20National%20Conference/ConferenceProceedings/Volume%201/Vol1final.pdf.

10.5.2 Workshops Conducted

Daly, C., M. Halbleib, and L. Eaton. 2013. “Nationwide Bio-Fuel Resource Mapping: Energycane Biomass Feedstocks.” Organized and conducted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Jackson, MS, May 7–8.

———. 2013. “Nationwide Bio-Fuel Resource Mapping: Switchgrass Biomass Feedstocks.” Organized, conducted, and hosted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Corvallis, OR, May 29–30.

———. 2013. “Nationwide Bio-Fuel Resource Mapping: Sorghum Biomass Feedstocks.” Organized and conducted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Oak Ridge National Laboratory, Oak Ridge, TN, June 27–28.

———. 2013. “Nationwide Bio-Fuel Resource Mapping: CRP Grass Biomass Feedstocks.” Organized and conducted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Kansas City, MO, July 25–26.

———. 2013. “Nationwide Bio-Fuel Resource Mapping: Woody Biomass Feedstocks.” Organized, conducted, and hosted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Corvallis, OR, September 18–19.

———. 2014. “Nationwide Bio-Fuel Resource Mapping: Miscanthus feedstocks.” Organized and conducted workshop for the U.S. Department of Energy/Department of Agriculture/Department of Transportation Sun Grant Initiative, Chicago, IL, February 18–19.

10.5.3 Presentations and Panels

Daly, C. 2011. “Biomass Mapping of Bio-Energy Feedstocks.” Presented at the U.S. Navy Green Fleet workshop, Honolulu, HI, March 7.

———. 2011. “Nationwide Bio-Fuel Resource Mapping: Estimating the Potential Distribution and Yield of Biomass Crops.” Presented at Texas A&M University Biomass Group, June 10.

———. 2013. “An Update on the PRISM-RMA Crop Suitability Mapping, and Weather and Climate Web Portal.” Presented to the U.S. Department of Agriculture Risk Management Agency–Davis regional and compliance offices, Davis, CA, December 11.

———. 2014. “An Update on the PRISM-RMA Crop Suitability Mapping, and Weather and Climate Web Portal.” Presented to the U.S. Department of Agriculture’s Risk Management Agency–Davis regional and compliance offices, Davis, CA, December 17.

Daly, C., and M. Halbleib. 2009. “Using Map Server Technology and Environmental Datasets for Feedstock Development and Assessment.” Presented at the Sun Grant Regional Initiative Energy Conference, Washington, D.C., March 12.

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11. Bioenergy Feedstock Library

11.1 Introduction

The Bioenergy Feedstock Library (the Library) was initially created to support the Partnership and is now a cornerstone tool for effectively evaluating the impacts of feedstock quality, formulation, and preprocessing activities on conversion performance. The Library supports the Partnership by bringing together disparate data associated with biomass feedstocks into a single management framework. Nearly 7,200 original biomass samples were cataloged from the Partnership. Building the Library to support the Partnership established a vision for what the Library could become, and laid the groundwork upon which many more sample management tools have been developed and continue to be developed.

The Library was initially developed as a system to track, house, and retrieve biomass feedstock materials created by the Partnership. It was structured to store and retrieve harvest and analytical characterization data.

The Library was developed with two primary objectives:

1. *Collect and manage samples:* The Library maintains a physical repository of biomass materials and process intermediates, which can be requested and used by Bioenergy Technologies Office researchers, industrial partners, universities, and government institutions around the world. The Library works with Partnership researchers as well as other bioenergy researchers to collect relevant samples for storage and dissemination and gathers data associated with these samples.
2. *Manage collected information*: The Library aggregates and organizes all available information about collected samples into a single, easily accessible database (bioenergylibrary.inl.gov). A web-based application is used to manage and access the information associated with the biomass samples. The information gathered related to biomass materials includes pedigree, agronomic, harvesting, and operations performed on the samples, such as drying and milling. The Library provides functions such as tracking and handling of materials, methods for entering and viewing data, and query capabilities for specific sample information, as well as methods to ensure the security of the stored data. In addition, the database tracks the analysis results for laboratory tests that have been performed on the samples. Analysis results can be used with Library research tools to interrogate data.

The Library sits at the center of many efforts to collect and distribute key information regarding feedstock quality characteristics to the bioenergy community as a whole. As shown in figure 11-1, the Library is a central resource for collecting, tracking, and distributing biomass and the data associated with it.

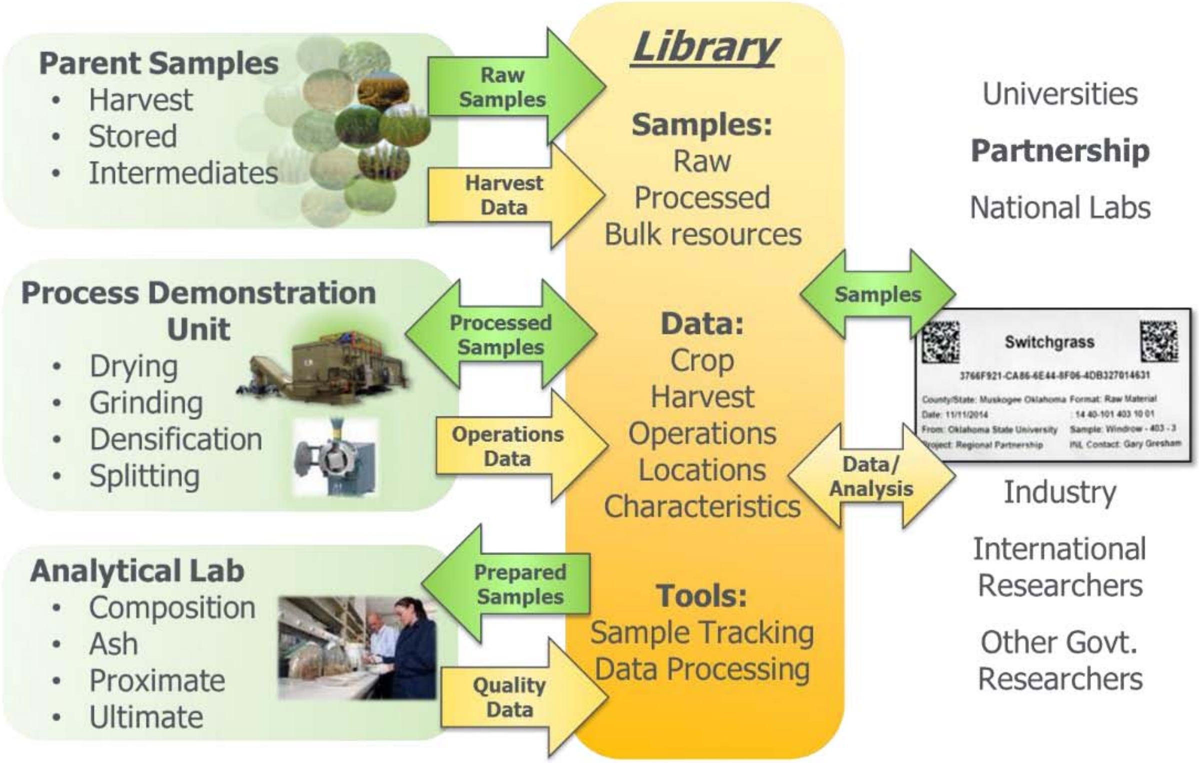

Figure 11-1 | The Bioenergy Feedstock Library, initially created to support the Partnership, is now one of the cornerstone tools of the U.S. Department of Energy's Bioenergy Technologies Office for effectively evaluating the impacts of feedstock quality, formulation, and preprocessing activities on conversion performance.

11.2 Impact of Partnership Library Data

The Bioenergy Feedstock Library has been instrumental to the analysis of quality for Partnership samples, and the results of this effort are significant for providing the bioenergy community with quality information from a comprehensive and unique sample set.

As of 2015, the Library hosts more than 30,000 physical samples (fig. 11-2) and has tracked more than 60,000 samples at various stages in the processing and collection of analytical data. The Library stores more than 1.5 million data points of physical history and characteristic metadata and more than 80,000 analysis data points.

The Partnership has contributed more than 20% of the original samples tracked in the Library (fig. 11-2). Of the approximately 3,000 publicly available biomass samples in the Library that have analytical data, the Partnership samples account for 90% (table 11-1). In addition, the Partnership initiative has improved the diversity of the unique types of biomass represented from 67 to 71 with the addition of native mixed grasses from the Conservation Reserve Program, energycane, wheat straw, and shrub willow. The Partnership samples also helped to increase the representation of locations across the nation increased by 10 states and 25 counties. The Partnership biomass types contributing to the increases in overall analytical data in the Library are shown in figure 11-3. A large portion of the analysis results described in table 11-1 are described in chapter 7, Impact of Feedstock Quality on Conversion and Yields.

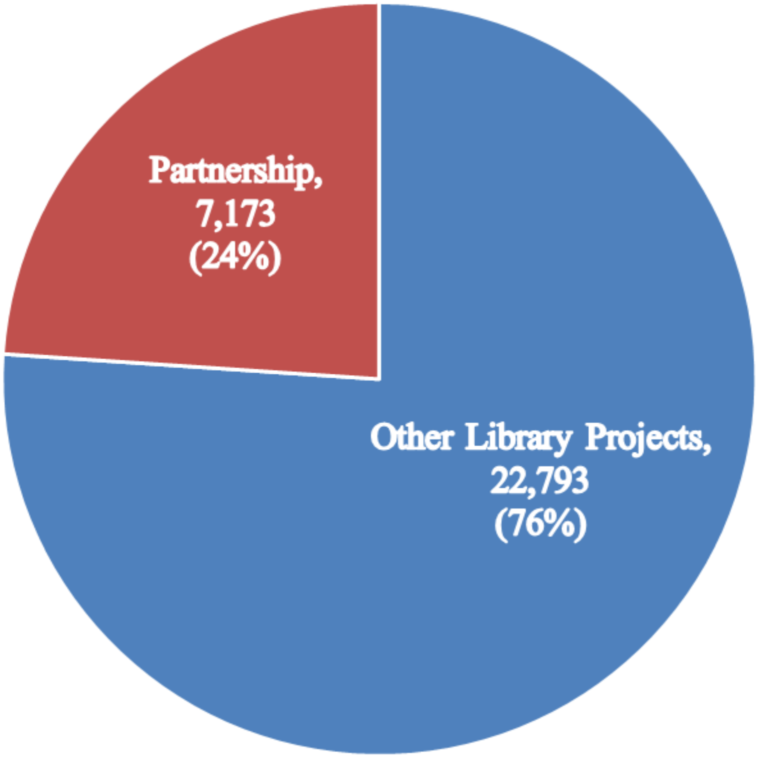

Figure 11-2 | Number of original samples contributed to the Library by project (2015).

Table 11-1 | Analyzed Sample Information and Primary Analysis Data for Samples from the Library in 2015

Sample information	**Other projects**	**Partnership**	**Total**
# Samples	393	2,896	3,289
# Biomass types	67	10	71
# States	23	25	33
# U.S. counties	35	31	58
Primary analysis information	**Other projects**	**Partnership**	**Total**
Ash	14	2,260	2,274
Compositional analysis	0	2,055	2,055
Proximate/ultimate	132	345	477

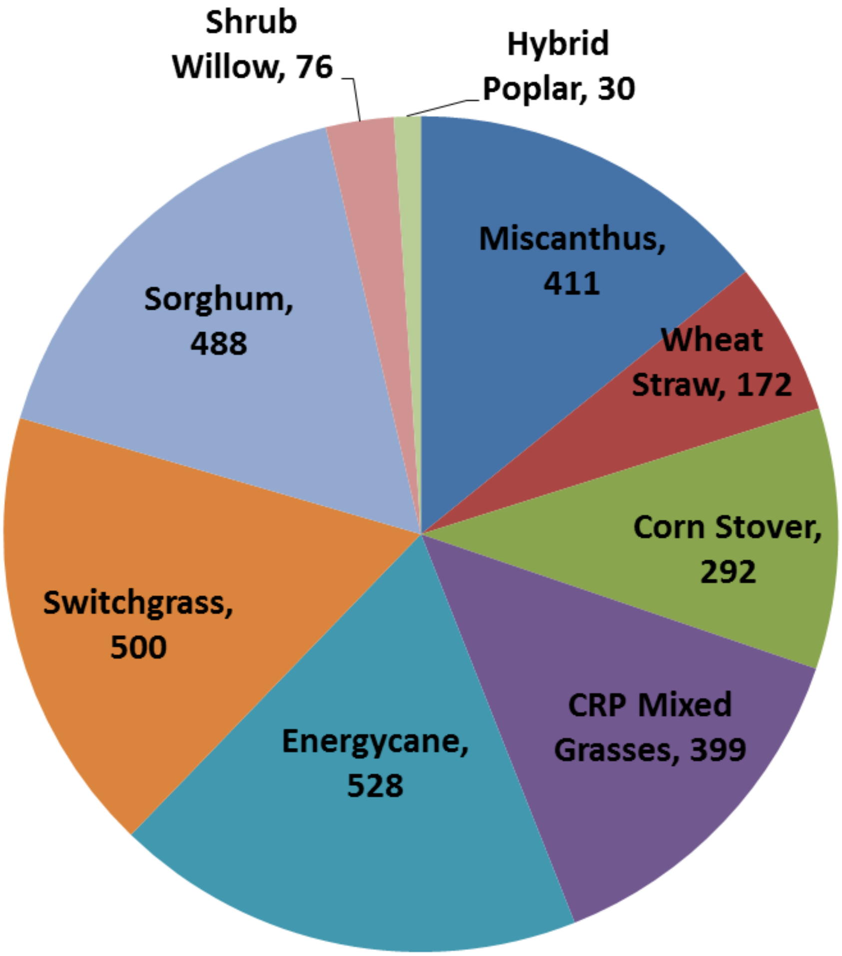

Figure 11-3 | Biomass type breakdown of 2,896 Partnership samples analyzed as of 2015.

11.3 Conclusion

The data in the Library, including data contributed from the Partnership, are used in many different research initiatives to make critical decisions for the bioenergy community, such as the following:

- Feedstocks best suited for a particular conversion pathway
- Locations of resources and their quality to meet the needs of industrial conversion facilities
- Sources of variability in key feedstock characteristics
- Predictions of blend characteristics that can inform further research and conversion experiments for reliable feedstocks meeting user-specified cost targets.

Although started as a mechanism to track Partnership samples, the Library continues to reach to a broader set of researchers to distribute essential information. The Library provides meaningful tools to researchers that will allow them to investigate the data and test different scenarios in an interactive way. Future work includes tools that will output information on variation in feedstock quality, including correlations with geographic location. New features will also enable enhanced administration by external research organizations, association of images with sample information, and easier upload of results for researchers around the globe, all in a secure platform based on roles and permissions for each set of data.

The reach and ongoing work of the Library will provide an even greater impact with the inclusion of the Partnership data. Data will be used to inform new research and will be combined with data from a larger research community to facilitate decisions and directions for the bioenergy industry as a whole.

11.3.1 Presentations and Panels

Emerson, R. 2016. “Quantifying Biomass Feedstock Variability Using the DOE Bioenergy Feedstock Library.” Presented at the Symposium on Biotechnology for Fuels and Chemicals, Feedstocks (III) Track, Baltimore, MD, April 27. https://sim.confex.com/sim/38th/webprogram/Paper31579.html.

———. 2016. “Quantifying Biomass Feedstock Variability Using the DOE Bioenergy Feedstock Library.” Presented at the Advanced Bioeconomy Feedstock Conference, Feedstocks for the Bioeconomy Panel Discussion, Miami, FL, June 8.

———. 2016. “Regional Feedstock Partnership: DOE Bioenergy Feedstock Library.” Presented at the Regional Feedstock Partnership Close-Out Meeting, Washington D.C., July 14.

Fox, C. 2016. “Building the DOE Bioenergy Feedstock Library as a Tool for Lignin Structure/Property Relationship Research.” Presented at the American Chemistry Society National Meeting, San Diego, CA, March 13.

11.3.2 Papers Citing Feedstock Library

Williams, C. L., T. L. Westover, R. M. Emerson, J. S. Tumuluru, and L. Chenlin. 2015. “Sources of Biomass Feedstock Variability and the Potential Impact on Biofuels Production.” *BioEnergy Research* 9 (1): 1–14. doi:10.1007/s12155-015-9694-y.