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Biomass production of herbaceous energy crops in the United States: field trial results and yield potential maps from the multiyear regional feedstock partnership

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Abstract

Current knowledge of yield potential and best agronomic management practices for perennial bioenergy grasses is primarily derived from small-scale and short-term studies, yet these studies inform policy at the national scale. In an effort to learn more about how bioenergy grasses perform across multiple locations and years, the U.S. Department of Energy (US DOE)/Sun Grant Initiative Regional Feedstock Partnership was initiated in 2008. The objectives of the Feedstock Partnership were to (1) provide a wide range of information for feedstock selection (species choice) and management practice options for a variety of regions and (2) develop national maps of potential feedstock yield for each of the herbaceous species evaluated. The Feedstock Partnership expands our previous understanding of the bioenergy potential of switchgrass, Miscanthus, sorghum, energycane, and prairie mixtures on Conservation Reserve Program land by conducting long-term, replicated trials of each species at diverse environments in the U.S. Trials were initiated between 2008 and 2010 and completed between 2012 and 2015 depending on species. Field-scale plots were utilized for switchgrass and Conservation Reserve Program trials to use traditional agricultural machinery. This is important as we know that the smaller scale studies often overestimated yield potential of some of these species. Insufficient vegetative propagules of energycane and Miscanthus prohibited farm-scale trials of these species. The Feedstock Partnership studies also confirmed that environmental differences across years and across sites had a large impact on biomass production. Nitrogen application had variable effects across feedstocks, but some nitrogen fertilizer generally had a positive effect. National yield potential maps were developed using PRISM-ELM for each species in the Feedstock Partnership. This manuscript, with the accompanying supplemental data, will be useful in making decisions about feedstock selection as well as agronomic practices across a wide region of the country.

Keywords: bioenergy, biomass, Conservation Reserve Program, energycane, feedstock, Miscanthus, sorghum, switchgrass

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Introduction

Herbaceous dedicated energy crops including switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus* spp.), energycane (*Saccharum* spp.), and sorghum (*Sorghum bicolor*) will play an important role in future sustainable bioenergy feedstock production, as outlined first in the 2005 Billion Ton Study (U.S. Department of Energy, 2005) then in the 2011 Billion Ton Update (U.S. Department of Energy, 2011) and recently in the 2016 Billion Ton Report (U.S. Department of Energy, 2016).

Switchgrass has received the greatest attention among all the potential perennial herbaceous bioenergy feedstocks studied in the past three decades (Parrish & Fike, 2005). The outpouring of interest and research effort on this North American native species arose from its high productivity, broad adaptability, and suitability to marginal sites. These were key factors that led the U.S. Department of Energy to select switchgrass as a model energy crop (Kszos *et al.*, 2000).

Because of its high genetic diversity, switchgrass grows across an expansive native range, extending from Canada to Mexico and from the Atlantic Coast to the Sierra Nevada Mountains (Hitchcock, 1971). The species has both upland and lowland ecotypes, primarily classified by their preferred habitat. Although there is some overlap in site adaptation, upland ecotypes are better suited to higher, drier land forms, and at higher latitudes while lowland ecotypes generally perform better in deeper soils, wetter conditions, and at lower latitudes (Brunken & Estes, 1975; Sanderson *et al.*, 1996; Casler *et al.*, 2004). Lowland ecotypes are larger, more robust plants that often reach heights >3 m. Upland ecotypes generally are finer-stemmed and shorter, with thicker roots and longer root internodes. Because of greater yield potential, lowland ecotypes are of interest where they are adapted for bioenergy production. However, upland ecotypes may be better suited for much of the available production area in North America, which is typified by cooler temperatures and drier conditions.

Miscanthus × *giganteus* Greef & Deuter ex Hodkinson & Renvoize is a large (up to 4 m) perennial grass grown as a bioenergy crop in Europe and the United States. Originally discovered in Japan in 1935, the parents of this sterile triploid hybrid are the fertile diploid *M. sinensis* and tetraploid *M. sacchariflorus* (Hodkinson *et al.*, 2002). The hybrid was initially used as a landscape plant, first in Europe and later in North America. *Miscanthus* × *giganteus* has been studied as a bioenergy crop in trials in Europe since 1983 (Lewandowski *et al.*, 2000) and in the United States since the early 2000s (Heaton *et al.*, 2004). Impressive biomass yields up to 40 Mg ha^{-1} in some European locations (Miguez *et al.*, 2008) have been reported, with mean yields of

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22 Mg ha^{-1} throughout the continent (Heaton *et al.*, 2004). In the United States, yields from small-scale plots have ranged from 35 Mg ha^{-1} (Heaton *et al.*, 2008) to 63 Mg ha^{-1} (Smith *et al.*, 2015). However, it is unknown whether field-scale plantings could reach these yields in the United States, particularly across varied environmental conditions. Yields from US studies typically average about 23 Mg ha^{-1}, but much lower values have also been reported (e.g., 4.5 Mg ha^{-1}, Lee *et al.*, 2014). Yields of 20–24 Mg ha^{-1} would be desirable, if such yields could be sustained across locations and years. Additional data were sought as part of the Feedstock Partnership to determine the locations, climates, and agronomic practices required to achieve optimum yield goals.

Sorghum (*Sorghum bicolor* L. Moench) has emerged as an important bioenergy crop for several reasons. First, it is an annual species amenable to normal crop rotations. The annual nature of the crop means that it can also be used to rapidly replace losses of perennial crops when stands are unexpectedly lost. Second, energy sorghum is widely adapted and highly amenable to U.S. production and cultivation systems, and under optimum conditions, current energy sorghum hybrids can produce up to 40 Mg of biomass per hectare (Rooney *et al.*, 2007; Mullet *et al.*, 2014). In addition, energy sorghum has excellent drought tolerance and high water use efficiency (Mullet *et al.*, 2002; Sanchez *et al.*, 2002; Buchanan *et al.*, 2005). Third, sorghum has an extensive history of cultivation and is supported by pre-existing production infrastructure and numerous breeding programs that develop new hybrids (Rooney, 2004).

Among energy crops, sorghum is unique because different types produce economic quantities of starch, sugar, and lignocellulosic biomass. Consequently, several types of sorghum can be used for biofuel or bioproduct production. Grain sorghum is used to produce ethanol in geographic regions where economics and supply allows it (Wang *et al.*, 2008). Energy sorghum types accumulate high biomass yields because they are photoperiod sensitive, meaning that flowering is delayed in long-day environments, which results in a longer vegetative growth period (Rooney & Aydin, 1999; Rooney *et al.*, 2007; Olson *et al.*, 2013). These types of sorghums are designed to produce biomass for lignocellulosic ethanol conversion programs (Packer & Rooney, 2014). Last, sweet sorghum contains high concentrations of fermentable sugar in a juicy stalk. Like sugarcane (*Saccharum* spp.), this juice can be extracted and fermented directly into ethanol and the bagasse can be used to make bioproducts from the remaining cellulose, hemicellulose, and lignin or burned for power generation.

Sugarcane is bred for large stalk diameter, low fiber content, and high sugar content. The northern limits of current sugarcane varieties have always been determined by the tropical origins of their parents. During the 1960s, mosaic virus threatened the sugarcane industry in Louisiana. The USDA-ARS Sugarcane Research Unit at Houma imported wild cane (*Saccharum spontaneum*) from the Himalayas and screened it for resistance to mosaic virus (Hale, personal communication). Along with the mosaic virus resistance from the *S. spontaneum* parent, there were other stress tolerances, including cold tolerance. In the 1970s, Louisiana State University made crosses and selected hybrid progeny of sugarcane × *S. spontaneum* for biomass and high fiber content, releasing L79-1002, an 'energycane' specifically as a biomass feedstock (Bischoff *et al.*, 2008). The Sugarcane Research Unit continued to make crosses and selections throughout the 1990s, and added cold hardiness to the list of desirable traits. Energycane, like sugarcane, is a tropical perennial that is vegetatively propagated. A crop can be harvested and grows back from the crown the year after. Unlike most other summer crops, energycane is established in the fall from mature canes of existing plants. As energycane is vegetatively propagated, vigor observed in F_1 hybrids of the original cross is maintained. Establishment of a field follows the same process as commercial sugarcane. Mature canes (seedcane) of the desired genotype are harvested in August or September. Being tropical in origin, energycane does not undergo a natural senescence. Growth slows in the fall because of cooler temperatures, but a killing frost is required to stop growth.

Conservation Reserve Program (CRP) lands having mixed perennial grasses are a potential source of biomass for cellulosic biofuel production. According to the Billion Ton Update, up to 10 million ha of CRP land could be used to produce 50 million Mg of dry bioenergy feedstock annually (USDOE, 2011). The CRP is a voluntary cost-share and land rental program established by the Food Security Act of 1985 (1985). The primary goal of the program is to protect environmentally sensitive lands by removing them from conventional crop production and establishing perennial plants for groundcover and wildlife habitat. However, CRP lands have declined by 34% over the past 10 years due to higher grain prices (Fargione *et al.*, 2009; Secchi *et al.*, 2009; Wright & Wimberly, 2013), and qualifying biomass feedstock cannot be sourced from land cleared after December 19, 2007 according to the Renewable Fuel Standard (EISA, 2007; USDA, 2010; Schnepf & Yacobucci, 2013). Managed haying of CRP land with contracts approved prior to July 28, 2010 may be conducted, but several stipulations exist, including, frequency of no more than once every 3 years, for a period of no longer than 90 days, typically July 16 through September 30, outside of the primary nesting season, on no more than 50% of contiguous fields in any given year, and on eligible land, excluding, for example, land within 30.5 m of a stream or permanent water body (Farm Security and Rural Investment Act of 2002; USDA-FSA, 2014). In addition, landowners have incurred a 25% reduction in CRP rental payments on hayed acres, and hay can be used on-farm or sold as animal feed or biomass (USDA-FSA, 2011). Best management practices for producing biomass on CRP land need to be established in order to ensure high yields, stand longevity, and grower profitability.

The 2011 Billion Ton Update summarized many plot-scale studies and concluded that dedicated energy crops including perennial grasses such as switchgrass, Miscanthus, and energycane, and annual crops such as sorghum, offer great potential for sustainable biomass production. In addition, the 2011 USDA regional roadmap (U.S. Department of Agriculture, 2010) identified the U.S. southeast and central east as major regions for feedstock production using these grasses.

However, clear management guidelines and field-based yield estimates are lacking for some of these crops, especially at realistic scales (farm, local, and regional). In 2008, the US DOE/Sun Grant Regional Feedstock Partnership (hereafter the Feedstock Partnership) began testing herbaceous feedstocks across the landscape in many states in the contiguous United States as well as Hawaii. Work on these species has taken place at the subfield to subwatershed scale, and the larger research areas include various topographic positions on the landscape. Willow shrubs (*Salix* spp.) and hybrid poplar (*Populus* spp.) were also included in the Feedstock Partnership work, and results from these trials are reported in Volk *et al*. (2017).

The objectives of the Feedstock Partnership studies were to (1) provide a wide range of information for feedstock selection (species choice) and management practice options for a variety of regions and (2) develop national maps of potential feedstock yield for each of the herbaceous species evaluated. For objective 1, this study discusses empirically derived yield potential as well as certain management practices that affect yield (e.g., cultivar selection, establishment, fertility, and harvest timing). For objective 2, yield potential maps were developed through an iterative process using the PRISM Environmental Limitation Model (PRISM-ELM) (Daly *et al*., 2017) and based in part on field research data (both small plot and field scale) obtained from Feedstock Partnership trials. In addition, the summarized raw data from these trials are provided as a supplement to this study, and the full dataset is accessible via the Knowledge Discovery Framework (KDF; U.S. Department of Energy Bioenergy KDF/https://www.bioenergykdf.net).

Materials and methods

Switchgrass

An 8-year field study (2008–2015) was completed as part of the Feedstock Partnership. A wide range of sites was chosen for this study to take advantage of switchgrass' broad adaptability, with large differences in geography, climate, and soil conditions. Fike *et al*. (2017) provide detailed information for each site including soil description, latitude and longitude, plot size, total annual precipitation, average daily temperature, previous crop, planting date, cultivar selection, and average annual biomass production. This information was relevant for understanding potential bioenergy schemes across the United States and also provided information for geospatial modeling. Switchgrass field trials were located in Elmore County, AL; Story County, IA; Tompkins County, NY; Muskogee County, OK; Day County, SD; and Pittsylvania County, VA. With the exception of the IA location, land at these sites was generally considered marginally productive for commodity crops relative to other sites in the region due to edaphic and topographic conditions. Reasons for marginal production varied by location but included poor drainage (OK and NY), slope (SD), and soil type (VA).

Switchgrass cultivars varied by site and choices were based on our understanding of productivity, site adaptation, and seed availability. Northern locations were planted to upland cultivars 'Cave-in-Rock' (IA and NY) and 'Sunburst' (SD). 'Blackwell', a regionally derived and adapted upland cultivar, was planted in OK because seeds of lowland ecotypes were not readily procurable due to other large-scale plantings occurring at the time. 'Alamo,' a broadly planted lowland ecotype that had been used in previous local and regional trials (Ma *et al*., 2001; Fike *et al*., 2006a,b; Bransby & Huang, 2014), was planted in AL and VA.

Switchgrass was planted at NY, OK, SD, and VA in 2008, IA in 2009, and AL in 2010. Initial fertility applications and first cropping year occurred the year after planting at all sites. All field operations (site preparation, planting, fertilization, and harvest) were conducted using commercially available equipment. Plot sizes were approximately 0.5–1.0 ha, and experimental treatments consisted of three nitrogen (N) rates (0, 56, and 112 kg N ha^{-1}). Nitrogen sources varied by site, but were limited to urea or ammonium sulfate. Treatments were replicated four times within sites. Biomass harvests in years following the year of establishment occurred as early as September (AL) and as late as March (VA) but most occurred in October or November, following a killing frost. The final crop year for this research occurred in 2015.

Miscanthus × giganteus

The 6-year field study (2010–2015) was repeated at five locations. *Miscanthus × giganteus* 'Illinois' (hereafter, Miscanthus) rhizomes obtained from the Chicago Botanic Garden were used

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to develop demonstration plantings at UIUC in 1988 (Maughan *et al.*, 2012), and rhizomes (~25 g ea.) harvested from the demonstration planting were propagated in UIUC greenhouses in spring 2008. In June 2008, potted plants were sent to all participating locations for hardening and transplanting. At the initiation of the project in 2008, the five participating sites in the Feedstock Partnership were the University of Illinois (Urbana, IL), Purdue University (West Lafayette, IN), the University of Kentucky (Lexington, KY), the University of Nebraska (Mead, NE), and Rutgers University (Adelphi, NJ). Due to high Miscanthus mortality and cooperator turnover, however, the Purdue University site was dropped following the planting year and replaced in spring 2010 with a Virginia Tech site in Gretna, VA.

At all sites, 100 Miscanthus plants were transplanted into each of twelve 10 m × 10 m test plots, a density that is in line with current practice and recommendations (Lewandowski *et al.*, 2000; Lee *et al.*, 2014). Irrigation and weed control were supplied as necessary to ensure establishment (Williams & Douglas, 2011; Lee *et al.*, 2014). In IL, due to severe winterkill during the 2008–2009 winter, 75% of the plants were replaced in spring 2009 to bring the number of live plants per plot back to 100.

Three nitrogen fertility treatments were applied (0, 60, and 120 kg N ha^{-1} using urea as the N source) in each location, and treatments were replicated four times. Planting and harvest dates were recorded, as were soil type, environmental data (precipitation, temperature), soil fertility (N, P, K), and biomass yield and moisture. The N treatments were applied annually thereafter.

Yields were determined by hand harvesting the aboveground biomass from 4 m^2 in the centers of each plot cut at 10 cm in IL, KY, NJ, and VA. Plots in NE were mechanically harvested. Harvest (fresh) weights were determined, and the dry biomass was measured by calculating the percent moisture of an oven-dried subsample. Harvests took place each year starting in 2009 between November and April following senescence, depending on weather, location, and year. The timing is in line with current practice in the Midwestern United States (Lee *et al.*, 2014).

Sorghum

A 5-year study (2008–2012) was conducted by the Feedstock Partnership. Six sorghum genotypes were evaluated in all seven environments over 5 years. The seven environments were chosen to represent diverse bioenergy sorghum production sites and included Manhattan, KS; College Station, TX; Corpus Christi, TX; Ames, IA; Lexington, KY; Raymond, MS; and Roper, NC. All yield trials were rainfed, and no irrigation was applied in any environment. Nitrogen was applied in each environment per recommended rates for forage sorghum production in the region. The six genotypes included five commercial hybrids and one sweet sorghum cultivar and are described in detail by Gill *et al.* (2014). Most of these sorghums were not specifically developed for bioenergy. In all environments, a randomized complete block design was used, but plot size and number of replications varied across locations. Agronomic practices standard for each location were used. Agronomic traits evaluated at each location included fresh weight of total biomass, moisture concentration of the biomass, and dry weight of biomass. Fresh weight was measured in the field, while moisture content was determined by drying a freshly harvested sample, drying it to stability in a forced air oven at 70 °C, and then reweighing the sample. Dry weight on an area basis was estimated by multiplying fresh yield by the dry matter concentration of the dried sample.

Energycane

A 7-year field study (2009–2015) was completed as part of the Feedstock Partnership. Five energycane lines provided through an agreement with USDA-ARS Sugarcane Research Unit (Houma, LA) tested from 2006 to 2008 at Mississippi State, MS, were selected for broader testing across the Southeast and Hawaii as part of the Feedstock Partnership (Baldwin *et al.*, 2012). These genotypes were as follows: Ho02-147, Ho02-144, Ho72-114, Ho06-9001, and Ho06-9002. During the late summer of 2008, seedcane was distributed to seven test sites (Tifton, GA; Auburn, AL; Raymond and Mississippi State, MS; St. Gabriel, LA; Beaumont and College Station, TX). Crop failure at the Auburn site caused an alternate site to be selected at Athens, GA. Waimānalo, HI, was added in 2009. As these hybrids were newly created, little was known concerning the area of adaptation and cold hardiness. Athens, GA, and Mississippi State, MS, were the most northern locations (33° N latitude). As germplasm was limited, field size was restricted. Individual genotypes were planted in plots 9.75 m long × 3 rows (5.5 m) wide. Fields were maintained under the recommendations for sugarcane production (LSU, 2014). Fertility recommendations were to maintain soil pH of 6.5 and application of 112 kg N ha^{-1} at northern locations, while southern locations applied up to 150 kg N ha^{-1} depending on soil tests.

During subsequent years, emergence data, height, °Brix (a measure of soluble carbohydrates), and aboveground biomass were recorded. Harvest date varied by location, depending on frost and local weather conditions. Dry stalks were ground and submitted for structural carbohydrate analysis (cellulose, lignin, and sugar). During summer 2015 and 2016, the continental sites were in their sixth ratoon crop (7 years of data). Hawaii, which joined the program in 2009, was reporting its fourth ratoon crop. Yields for Waimānalo, HI, and St. Gabriel, LA, were converted to dry weight from cane weight (fresh harvested yield) by multiplying fresh weight by percentage fiber.

Conservation Reserve Program (CRP) grassland

A 6-year field study (2008–2013) was conducted through the Feedstock Partnership on established CRP lands at six sites that represented CRP grassland distribution in the United States (Lee *et al.*, 2013; Anderson *et al.*, 2016). Three of the sites—Ellis County, KS, Jackson County, OK, and Foster County, ND—were planted to predominantly warm-season grass mixtures, and the other three sites—Judith Basin County, MT, Oconee County, GA, and Boone County, MO—to cool-season grass mixtures. In addition to grass species, legume species were also present at MT, MO, and KS. All locations had been managed according to CRP regulations with no nitrogen (N) fertilization and no biomass harvested. Plot size was 0.5 ha to better approximate farm-scale conditions. Existing biomass was mowed and treatments were first applied in the spring of 2008.

The experiment was designed as a factorial of three N rates (0, 56, and 112 kg N ha^{-1}) applied annually, and two harvest timings (at peak standing crop, PSC, and at the end of the growing season, EGS, after a killing frost) within a randomized complete block with three replications at each site. Species composition was estimated annually in June or July. Biomass was harvested from the entirety of each plot with a farm-scale harvester at the prescribed timings. The PSC harvest timing was determined at each location by the occurrence of anthesis of the predominant species. Warm-season mixture sites were harvested at PSC near the end of summer or at EGS after a killing frost. Harvest timing for cool-season mixture sites varied among sites, with MT plots being harvested at PSC in early summer or at EGS in the fall. All plots in GA were harvested in the spring, and the EGS treatment plots were also harvested in the fall in a two-cut system. All treatments in MO were two-cut systems, with PSC plots being harvested in midspring and again in the fall, and EGS plots being harvested in early summer and in the fall. Biomass at all locations was baled with a large round baler.

Yield potential maps

The resource mapping approach was designed to take advantage of the informational synergy realized when bringing together three components—coordinated field trials, expert opinion, and spatial modeling—into a single, collaborative effort. The first component consisted primarily of field trials of the herbaceous crops described above. The second component included face-to-face interactions between the modeling group and the Feedstock Partnership agronomists conducting the field trials. The third component was a biogeographical modeling and mapping system called PRISM-ELM (Parameter-elevation Regressions on Independent Slopes Model-Environmental Limitation Model). PRISM-ELM is described in detail in Daly *et al.* (2017). Briefly, PRISM-ELM is a statistical-mechanistic model that encompasses both empirical and mechanistic techniques to develop projections of potential yield based on climate and soil parameters. This model was selected because it can generate potential yield maps for a range of different cropping systems over broad regions without requiring detailed data on plant characteristics and physiology. PRISM-ELM was designed to answer a basic question: How do climate and soil characteristics affect the spatial suitability and long-term production patterns of a given crop? It employs a simple water balance to simulate the correspondence, or lack thereof, between water availability (based on precipitation and soil moisture) and growing season timing (based on a temperature response curve). The model uses simplified metrics to represent complex processes. January mean minimum temperature and July mean maximum temperature are used to identify areas that have cold- or warm-season temperature extremes that may be unsuitable for meaningful crop production. Soil pH, salinity, and drainage response curves also serve as metrics for unsuitable soil conditions. The focus is on a general approach to model climatic and soil constraints on biomass production for any crop, rather than a detailed accounting of the particular phenology or other morpho-physiological features of a given species or genotype. Suitability maps estimated by PRISM-ELM were transformed into yield potential maps through statistical regressions between the level of environmental suitability and biomass yield data from the Feedstock Partnership field trials.

Results

Switchgrass

Large yield variation was observed among sites over the course of the study—not unexpected given the range of sites, site conditions, and cultivars included in this research (Fig. 1; Table S1). In the first production year (i.e., the year following the planting year), yields ranged from 1.26 (SD) to 7.88 (NY) Mg ha^{-1}. Variation within sites—even over the three N rates—generally was not as great as site-to-site variability.

Average yields over the first 3 years of production in AL, IA, and NY were 10.7, 7.8, and 7 Mg ha^{-1}, respectively, but yields for the remaining sites during this time period were in the 4–6 Mg ha^{-1} range. Yields also increased over the first few production years at most sites, but they were more stable over time in IA, NY, and SD. For example, during the last 3 or 4 years of the study, average yields in IA, NY, and SD were 8.0, 7.8, and 4.5 Mg ha^{-1}, respectively, representing increases of about 3–13%. In contrast, yields between these time periods increased over 50% in OK (5.5 vs. 8.3 Mg ha^{-1}) and 34% in VA (6.1 vs. 8.2 Mg ha^{-1}).

Switchgrass response to N was highly variable, but greatest in SD and VA. These two locations had the lowest initial soil N (Owens *et al.*, 2013), with levels through the profile only 62% (SD) and 30% (VA) of average profile N levels of the other sites. At these two sites, large production responses to N were observed in the initial production years (2009–2012; Hong *et al.*, 2014), and over all the production years the percent yield increase in response to N (highest N treatment vs. control) averaged 57% in SD and 76% in VA. In contrast, the average yield increases in AL (where some of the highest yields were recorded) was about 13%. In OK and NY, there was no benefit of added N across years, and in some production seasons, the effects of N on switchgrass in NY were significantly negative. The response pattern in IA was unlike that in other locations in that the response to N was limited in the first few years of production, but by the fourth

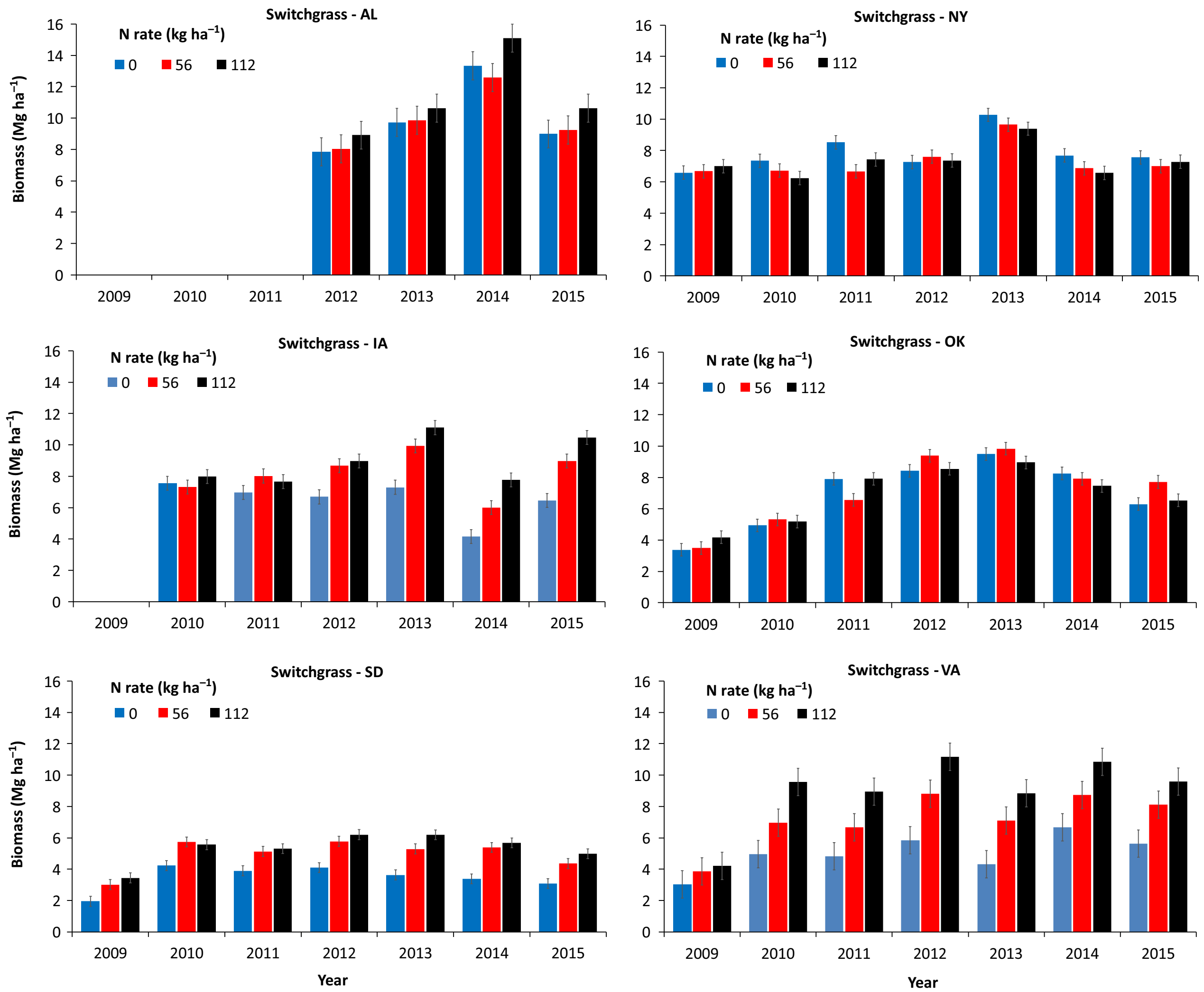

Fig. 1 Average annual dry biomass yield of switchgrass in response to three N rates at six locations across the United States between 2009 and 2015. With the exception of the AL location, yield data were collected beginning the year after planting. The AL location experienced stand failure in 2008 and 2009, and yield data were not collected until 2012. The IA location was not planted until 2009. Bars represent standard errors of the differences in means when analyzed by location (α = 0.05).

through sixth years the yield increase with high N averaged 67%.

PRISM-ELM yield estimates

In addition to field studies, switchgrass field researchers and scientists from Oak Ridge National Laboratory met with the Oregon State University PRISM-ELM Climate group to develop maps of switchgrass yield potential across the United States based on data gathered from these field trials and from previous work (Fig. 2). Average relative maximum yield for lowland ecotypes was 22 and 13 Mg ha^{-1} for upland ecotypes. Modeled yields confirm the yield advantage of lowland ecotypes, specifically in the southeastern United States. They also demonstrate the wide adaptability of upland ecotypes east of the 100th meridian.

Miscanthus × giganteus

In IL, KY, NE, and NJ, average yields across all fertility treatments from 2010 to 2015 were 18.1, 15.3, 24.7, and 16.5 dry Mg ha^{-1}, respectively, and 17.3 dry Mg ha^{-1} for VA, 2012–2015. Miscanthus typically approaches plateau yields in two to five growing seasons (Zub & Brancourt-Hulmel, 2010), and we chose year three to begin our reporting.

There were productivity differences among sites and years, and thus, each site and year was analyzed separately. There were no effects from N applications in

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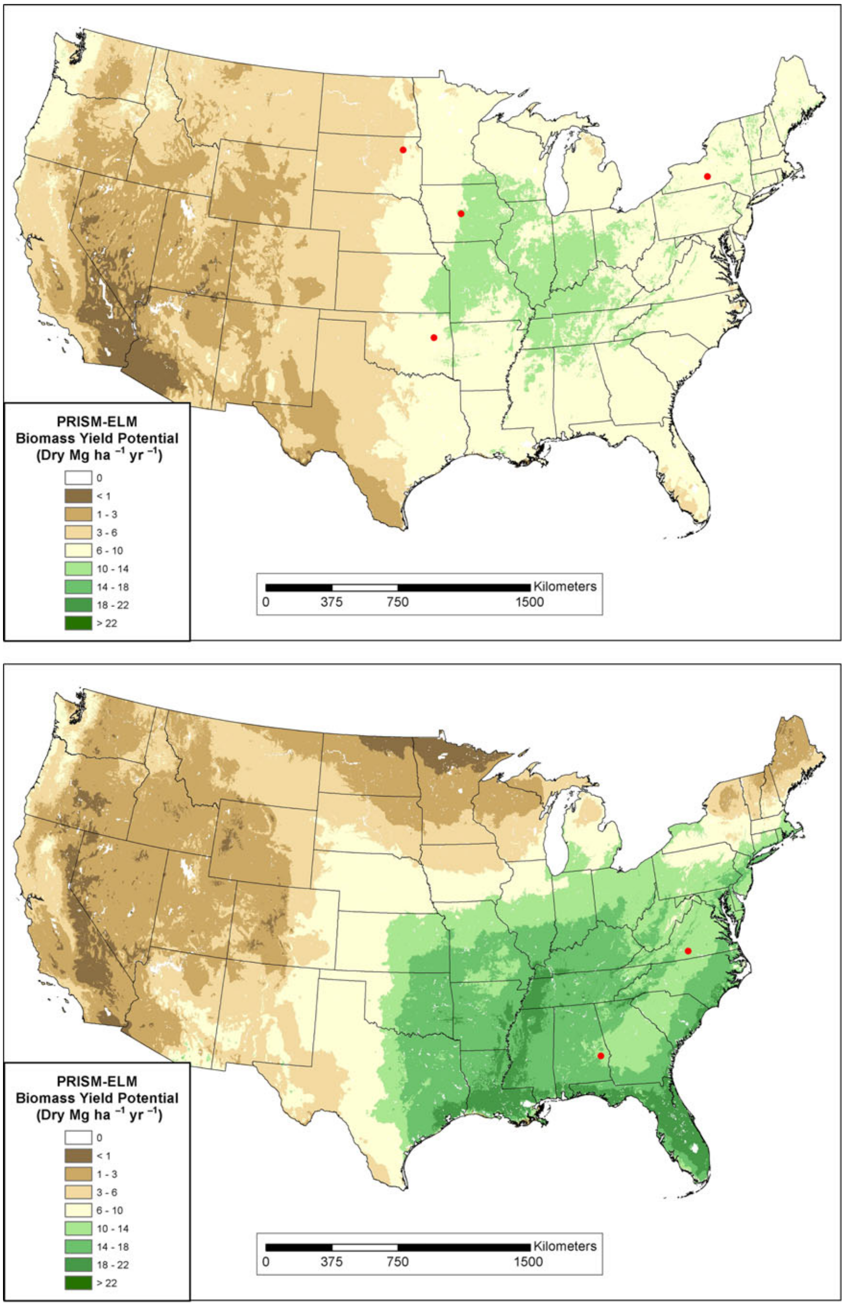

Fig. 2 Biomass yield potential of upland (top) and lowland (bottom) switchgrass for the United States generated using the PRISM-ELM model and based in part on Regional Feedstock Partnership Field Trials (red dots).

growing years three and four at any site (Fig. 3; Table S2). Nitrogen fertilizer applications did not affect productivity in any year in KY. In most cases, when N fertilizer application affected productivity, the fertilized plots were more productive than the unfertilized plots and there were no productivity differences between the 60 and 120 kg N ha^{-1} (IL, 2012–2015; NJ, 2013; and VA, 2014 and 2015). In NJ (2014), the 120 kg N ha^{-1} treatment was more productive than the 0 and 60 kg N ha^{-1} treatments, and in NE (2015), only the 120 kg N ha^{-1} treatment was more productive than the 0 kg N ha^{-1} treatment (Fig. 3; Table S2). Across sites, 2012 was a lower-yielding year due to the severe drought in much of the study region. Most sites rebounded to predrought yields in 2013 or 2014.

PRISM-ELM yield estimates

PRISM-ELM maps were created using a 4-year average yield for the years 2009–2015 and regressed against the

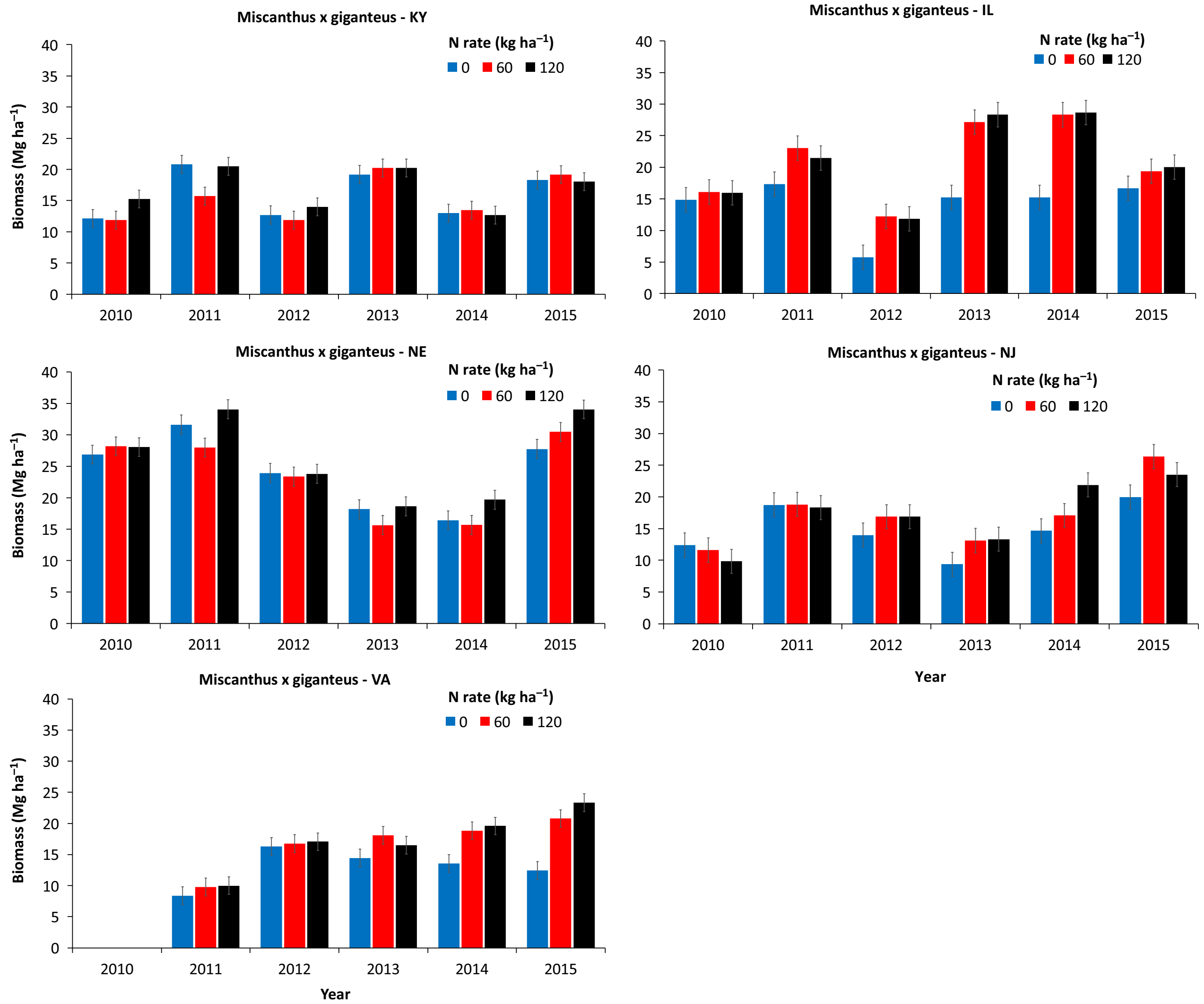

Fig. 3 Average annual dry biomass yield of Miscanthus in response to three N rates at five locations across the United States between 2010 and 2015. Miscanthus was planted from rhizomes in 2008 except at VA where transplanting occurred in 2009. Bars represent standard errors of the differences in means when analyzed by location ($\alpha = 0.05$).

actual yield values (Fig. 4). Our field data are well represented in the model results, although we did see higher yields than the model predicted in some years and locations (e.g., 2012 NE and 2014 NJ). However, it is important to note that the PRISM-ELM models are based on climate data averaged from 1981 to 2010, and that any spikes in particular years will be smoothed out due to averaging.

Although we did not carry out the study in all regions of the United States, field and modeling results indicate that earlier, outdated yield projection maps (Miguez *et al*., 2012) should be revised with greater regional suitability for Miscanthus, including an expanded east–west band in the north from NE to NJ (Fig. 4).

Sorghum

While variation was detected among genotypes, environmental conditions were the major factor affecting both biomass yield and composition in a given year and annual rainfall was the single most important variable. This was reflected in the wide variation in yield across years within a location (Table 1; Table S3). In fact, four environments were lost due to weather conditions (Table 1; Table S3). In general, the southeastern United States had the highest and most stable yields, indicating that this is the most stable region for sorghum biomass production (Table 1; Table S3). The variation among genotypes for dry biomass yield indicated that sorghum germplasm can be improved and that certain hybrids are more tractable for

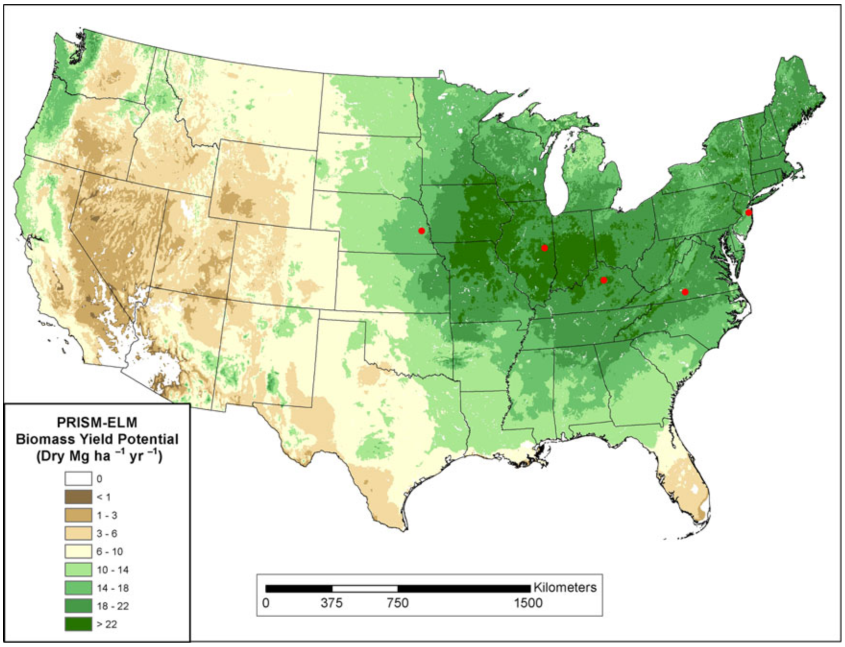

Fig. 4 Biomass yield potential of Miscanthus for the United States generated using the PRISM-ELM model and based in part on Regional Feedstock Partnership Field Trials (red dots).

Table 1 Annual dry biomass yield (Mg ha^{-1}) averaged over all six genotypes between 2008 and 2012

	Years					Location
Location	2008	2009	2010	2011	2012	average
Corpus Christi, TX	16.9		6.6	5.0	4.5	7.1e
College Station, TX	14.2	10.7	11.1	4.0	14.9	10.4d
Ames, IA		13.9	15.4	17.2	15.6	15.5b
Manhattan, KS	16.4	10.8	15.2	12.3		13.3c
Lexington, KY			15.1	12.2	22.8	17.3a
Raymond, MS	9.4	16.0	17.5	17.9	17.9	16.3b
Roper, NC		23.5	16.4	13.3	16.7	17.5a
Year average	14.1b	15.0a	13.6b	11.5c	15.4a	

The absence of yield data for a location and yield was due to environmental factors: Corpus Christi in 2009 (drought), Manhattan in 2012 (storm damage), Roper in 2008 (storm damage), and Ames in 2008 (wet weather prevented planting). Lexington, KY began testing in 2010.
Different letters in the Location Average column indicate statistical differences among the means at $P < 0.05$.
Different letters in the Year Average row indicate statistical differences among the means at $P < 0.05$.

biomass/bioenergy production. In fact, since study was initiated, numerous additional sorghum hybrids with improved agronomic performance for biomass production have been developed and are commercially available. In addition, dual-purpose sorghums, which combine both starch and cellulosic biomass production, have been integrated into some biomass conversion systems (Burks *et al.*, 2013). All of these developments occurring within a short time frame confirm the capacity of the sorghum improvement programs to make improvements in this annual energy crop.

PRISM-ELM yield estimates

Using data generated from the Feedstock Partnership trials as well as other yield data collected, and combined with basic growth parameters and weather data, the PRISM-ELM model for bioenergy sorghum indicates that sorghum has high yield potential across a wide range of the Central and Eastern United States (Fig. 5). Yields in the far northern United States (>42° N) trend lower due to the cooler temperatures and short growing season. In the southeast, while the productivity is high overall, the relative increases and reductions are associated with soil fertility and quality.

Energycane

As expected, energycane characteristics showed a location effect. Variety and year effects were also significant at all locations except Hawaii. Generally, yield increased from the onset of the test (2009) to 2011 and 2012, but then declined (Tables 2 and 3; Table S4). Notable exceptions to this were the Beaumont, TX, site which mistakenly applied twice the annual N rate during the final 2 years, and

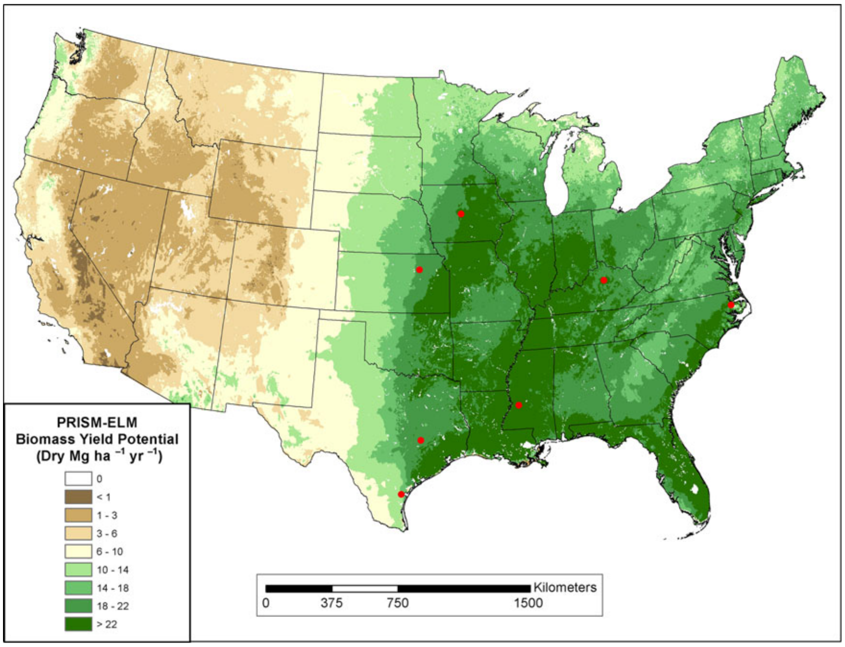

Fig. 5 Biomass yield potential of sorghum for the United States generated using the PRISM-ELM model and based in part on Regional Feedstock Partnership Field Trials (red dots).

Table 2 Dry biomass yield (Mg ha^{-1}) of five energycane genotypes tested at eight locations averaged over the 2009 to 2015 annual harvests

	Variety				
Location	Ho 02-144	Ho 02-147	Ho 06-9001	Ho 06-9002	Ho 72-114
Athens, GA	19.7 a*	15.9 b	20.8 a	20.6 a	14.0 c
Tifton, GA	23.8 c	25.5 c	31.0 a	32.1 a	28.5 b
Waimānalo, HI‡§	38.6 a	38.0 a	39.2 a	35.1 a	39.7 a
St. Gabriel, LA§	20.1 b	22.2 ab	23.7 a	20.5 b	22.3 ab
Raymond, MS	12.1 c	15.5 ab	15.2 abc	17.8 a	13.3 bc
Miss. State, MS	16.9 b	12.9 c	20.2 a	18.9 ab	12.6 c
Beaumont, TX	32.8 b	38.8 ab	42.1 a	39.5 ab	43.5 a
College Station, TX	22.4 ab	19.2 b	20.5 b	21.1 ab	24.4 a
Variety average	23.3 B†	23.5 B	26.6 A	25.8 AB	25.0 AB

*lowercase letters indicate significant differences among variety means within location at $\alpha = 0.05$.

†UPPERCASE letters indicate significant differences among variety means across all locations at $\alpha = 0.05$

‡Hawaiian location mean is a 5-year average.

§Dry weight values calculated by multiplying fresh weight by percentage fiber.

Mississippi State, MS, where yields continued to decline due to two below-average precipitation winters. While there were varietal differences by location, Ho 06-9001 had the greatest mean dry matter yield (MDMY) for seven of eight locations throughout the entire duration of the testing (Table 2). At College Station, Ho72-114 had the greatest MDMY. Lowest MDMYs were observed at Raymond (12.1 Mg ha^{-1}), Mississippi State (12.6 and 12.9 Mg ha^{-1}), and Athens (14.0 Mg ha^{-1}), which are the northern-most locations. It should be noted that both Beaumont and St. Gabriel are in traditional sugarcane growing regions.

Both Mississippi State and Athens showed similar patterns over the 7 years of this study. At both locations, the pithy type (Ho72-114) had the lowest MDMY across the 7 years, while the woody types (Ho06-9001 and Ho06-9002) had the greatest MDMY (Table 2). The intermediate true hybrids (Ho02-144 and Ho02-147) had a lower MDMY than the woody types, but were greater than the pithy type. At these northern locations, genotype yields ranged from 14.0 to 20.8 Mg ha^{-1} at Athens and 12.6 to 20.2 Mg ha^{-1} at Mississippi State (Table 2).

At Raymond, Ho06-9002 had the greatest mean DM harvested (17.8 Mg ha^{-1}), but was not different from Ho06-9001 and Ho02-147 (Table 2). Across years, MDMY (pooling entries) was at 14.8 Mg ha^{-1}, showing peak yields in 2009 and 2014 (Table 3).

At Tifton, Ho 06-9001 and Ho 06-9002 had the greatest average MDMY (Table 2). The Ho06-900X entries are woody types. Yields significantly decreased from 2012 through 2014 and then recovered in 2015 (Table 3). The reduction in 2013 and 2014 may have been partially due to a greater amount of rainfall and below-normal temperatures.

Table 3 Average annual dry biomass yield (Mg ha^{-1}) averaged over five energycane genotypes for eight locations between 2009 and 2015

Location	Year 2009	2010	2011	2012	2013	2014	2015	Location average
Athens, GA	8.3 e*	24.4 b	6.2 e	22.8 bc	30.5 a	13.9 d	21.3 c	18.2 CD†
Tifton, GA	29.2 c	29.5 c	34.0 b	39.8 a	22.1 d	14.7 e	27.9 c	28.1 AB
Waimānalo, HI‡§	–‡	–	37.4 ab	45.2 a	37.2 bc	41.0 ab	29.7 c	38.1 A
St. Gabriel, LA§	16.6 e	17.5 de	31.4 a	18.1 de	19.5 d	21.7 c	27.5 b	21.8 BC
Raymond, MS	17.5 a	12.3 b	11.6 b	13.7 ab	14.1 ab	17.5 a	16.8 a	14.8 D
Miss. State, MS	17.2 c	16.9 c	21.6 b	26.7 a	22.7 b	6.7 d	2.4 e	16.3 D
Beaumont, TX	-	46.3 a	30.7 b	30.0 b	28.5 b	50.3 a	50.2 a	39.3 A
College Station, TX	13.6 d	22.9 bc	16.1 d	26.8 b	22.3 c	17.6 d	31.3 a	21.5 BCD

*lowercase letters indicate significant differences among year means within location at $\alpha = 0.05$.
†UPPERCASE letters indicate significant differences among location means across all years at $\alpha = 0.05$.
‡Hawaii entered the Feedstock Partnership late due to legislation and quarantine.
§Dry weight values calculated by multiplying fresh weight by percentage fiber.

At a similar latitude to Tifton, but 1400 km west (at the 96th meridian), College Station had an overall MDMY for all genotypes of 21.5 Mg ha^{-1} (Table 3). Unlike the other sites, Ho06-9001 was not the highest yielding type; instead, Ho72-114 and Ho02-144 had the highest yields (24.4 and 22.4 Mg ha^{-1}, respectively) (Table 2). College Station was an irrigated site, and yield depended heavily upon available water. Mean dry matter yield of energycane genotypes increased 69% from 2009 to 2010 and again in 2011 and 2014 (Table 3).

The greatest continental yields were observed at Beaumont. Mean dry matter yield across all years was 39.3 Mg ha^{-1}. Mean dry matter yields in 2014 and 2015 were significantly greater than all other years (50.3 and 50.2 Mg ha^{-1}, respectively). These data would suggest the increased yields noted in 2014 and 2015 were due to an extra N fertilization event. From 2009 to 2013 and in 2015, 112 kg N ha^{-1} was applied in March, and 225 kg N ha^{-1} was accidently applied in April. In 2014, the crop received 112 and 225 kg N ha^{-1}, both applied in March, with a third application of 225 kg N ha^{-1} applied in April. In addition, rainfall during the 2015 growing season was substantially greater than the mean (115 vs. 77 mm, respectively).

In St. Gabriel, the greatest yields occurred in 2011 and 2015 (31.4 and 27.5 Mg ha^{-1}, respectively). When calculated over all years, Ho06-9001 had the highest numerical MDMY (23.7 Mg ha^{-1}), but it was not different from Ho02-147 and Ho72-114 (22.2 and 22.3 Mg ha^{-1}, respectively).

The only truly tropical site, Waimānalo, joined the program in 2009 because Hawaiian law prohibited the importation of new sugarcane germplasm until 2008. Propagation was delayed by heat treatments applied on the mainland to destroy pathogens, and the material was quarantined for one year. Waimānalo MDMY was significantly affected by year, but no significant differences were noted among cultivars. Being tropical in location, the Hawaiian site was not bound to seasonal harvest. Harvest increments cycled roughly 12 months. Generally, MDMY was the same from 2011 to 2014 and declined in 2015 (37.4, 45.2 37.2, 41.0, and 29.7 Mg ha^{-1}, respectively).

PRISM-ELM yield estimates

Energycane field scientists from all sites and modeling scientists from Oregon State University's PRISM Climate Group, as well as Oak Ridge National Laboratory, assembled together to generate the PRISM-ELM model for energycane (Fig. 6). Yield data from each location were combined with climatic parameters to determine an assessment of yield at locations across the southern United States. Looking at the figure, the PRISM-ELM model for energycane suggests highest yields would be expected in north central Florida and along the Gulf Coast. The second order yields would be expected with plantings south of 32° N and east of the 100th (W) meridian. The five genotypes of energycane were tested at 33° N. Initial dry matter yields were as high as Miscanthus and lowland switchgrass at the same location; however, dry matter yields declined with time due to relatively long winters and occasional cold weather (-12 °C) for longer than 72 h.

The model shows average dry matter yield over time. At every site, analysis of variance indicated year (winter temperature or precipitation) was a significant confounding effect. It should be noted that as energycane is planted farther north, it loses its yield advantage. Colder winters and shorter growing seasons of the 'northern' areas (>32° N) reduce the growing season for this tropical crop. Temperate biomass crops such as

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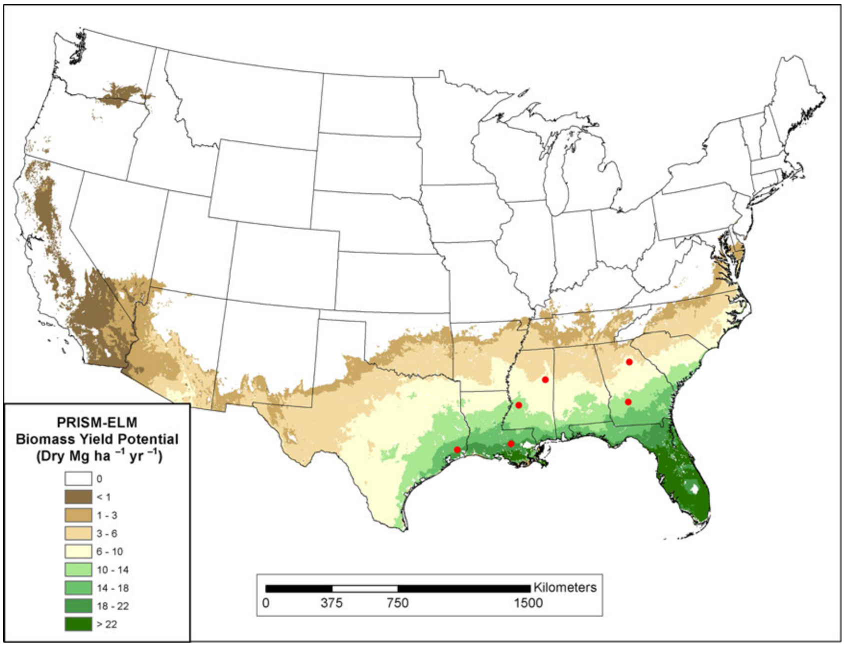

Fig. 6 Biomass yield potential of energycane for the United States generated using the PRISM-ELM model and based on in part on Regional Feedstock Partnership Field Trials (red dots).

Miscanthus and lowland switchgrass adapted to these latitudes exploit the reduced growing season and yield as much as energycane.

Conservation Reserve Program (CRP) grassland

Biomass yields are summarized in Fig. 7 (Table S5). Yield was significantly impacted by N rate, harvest timing, and year. Biomass yield increased as N fertilization rate increased, and applying 112 kg N ha^{-1} yr^{-1} was an agronomic best management practice (BMP) with respect to biomass yield. The harvest timing that resulted in the highest biomass yield over time was dependent on the mixture of plant species, the number of harvests taken (one- versus two-cut system), and the amount of precipitation received during the growing season. The BMP for harvest timing was site-specific, and biomass yields under N rate and harvest timing BMPs were 1.6–3.5 and 3.7–6.4 Mg ha^{-1} for warm- and cool-season mixtures, respectively, when averaged over time (Fig. 8). The effect of year on biomass yield was mainly attributed to the amount of precipitation received during the most critical period of the growing season, with most locations experiencing moderate to severe drought conditions for at

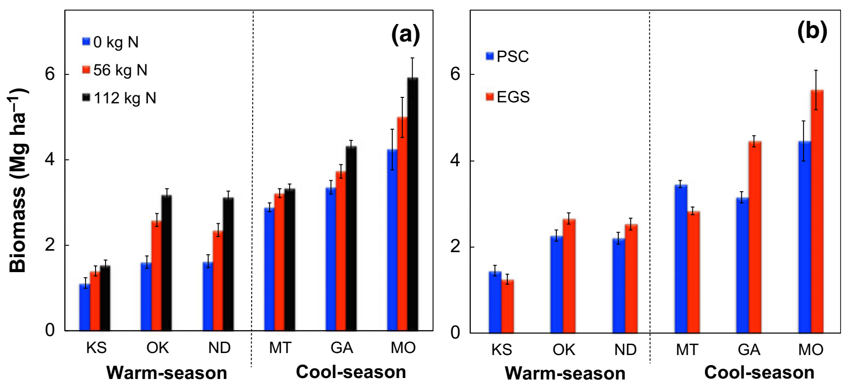

Fig. 7 Average annual dry biomass yield of mixed grasses in the Conservation Reserve Program lands as affected by (a) N rate and (b) harvest timing between 2008 and 2013. Yields were averaged across all harvest years. Harvest timings included peak standing crop (PSC; at anthesis) and end of the growing season (EGS). Bars represent standard errors of the differences in means when analyzed by location ($\alpha = 0.05$).

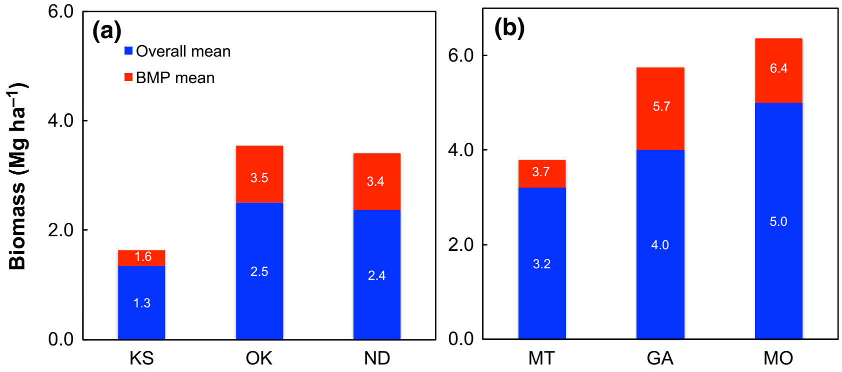

Fig. 8 Average annual dry biomass yields of (a) warm-season and (b) cool-season grasses on Conservation Reserve Program lands between 2008 and 2013. Overall mean yields were averaged across years, N rates and harvest timings, and best management practices (BMP) were site specific and based on the harvest timing (peak standing crop at KS and MT, end of the growing season at other sites) and N rate (112 kg N ha^{-1} at all sites) with the highest mean dry biomass yield over time. Bars represent standard errors of the differences in means when analyzed by location (α = 0.05).

least one season. This effect of year, and precipitation in particular, highlighted the importance of conducting long-term field studies to more accurately predict expected biomass yields from CRP lands.

Of the three sites (MO, KS, and ND) that collected sufficient species composition data, MO and KS had fairly high percentages of legume (clover) species at the beginning of the study (28.8% and 27.2%, respectively) (Lee *et al.*, 2013). Nitrogen fertilization negatively affected legume composition at both sites, with higher N rates resulting in significantly lower legume representation. For example, legume composition at MO was lower after only 1 year of N application at 112 kg N ha^{-1}. Best management practices for N fertility will need to be determined for each location based on the mixture of plant species, particularly when legumes are present. With respect to harvest timing, warm-season grass composition tended to be higher with EGS harvests, particularly switchgrass (*Panicum virgatum* L.) and little bluestem (*Schizachyrium scoparium* (Michx.) Nash) at KS and switchgrass and big bluestem (*Andropogon gerardii* Vitman) at ND. This is not unexpected, as most warm-season grass species are fully active and in the reproductive stages during the PSC harvest window, which is one of the reasons for the recommendation of delaying harvest until after the plants have sufficiently translocated nutrients to the belowground overwintering structures.

PRISM-ELM yield estimates

The PRISM-ELM map of feedstock production potential of the CRP grassland was created based on data generated from the Feedstock Partnership field trials (Fig. 9), using field-scale production management practices. The PRISM-ELM model well represented the biomass yield potential of the CRP grassland estimated from the Feedstock Partnership field trials. As the CRP grasslands were not established for biomass production, data from both the field trials and the PRISM-ELM model indicated the feedstock production potential of the CRP grassland is <4 Mg ha^{-1}.

Discussion

Switchgrass

Switchgrass yields in these field settings did not reach the levels often reported from small plot studies (Muir *et al.*, 2001; Vogel *et al.*, 2002; Guretzky *et al.*, 2011; Rogers *et al.*, 2012). In some cases, initial yields were hampered by factors that hindered establishment. In particular, weed pressure at the VA and SD locations resulted in stand density percentages below 30% the first year after planting (Fike *et al.*, 2017); however, these stands improved over time as is commonly the case with switchgrass. Stand failure occurred over two consecutive years at the AL location, likely due to residual herbicide in the soil that was not known to the researchers. Utility of marginal land for energy production systems remains questionable given challenges for establishment and yields that may be lower than desirable. The subpar establishment rates that arose at several sites in this study would negatively influence economic outcomes in a real-world setting and point to challenges for deploying biomass systems on marginal sites with difficult edaphic conditions, seed banks laden with weed seeds, or both. Although manageable, these issues present additional costs in terms of lower yield with the slow establishment or the cost of weed control.

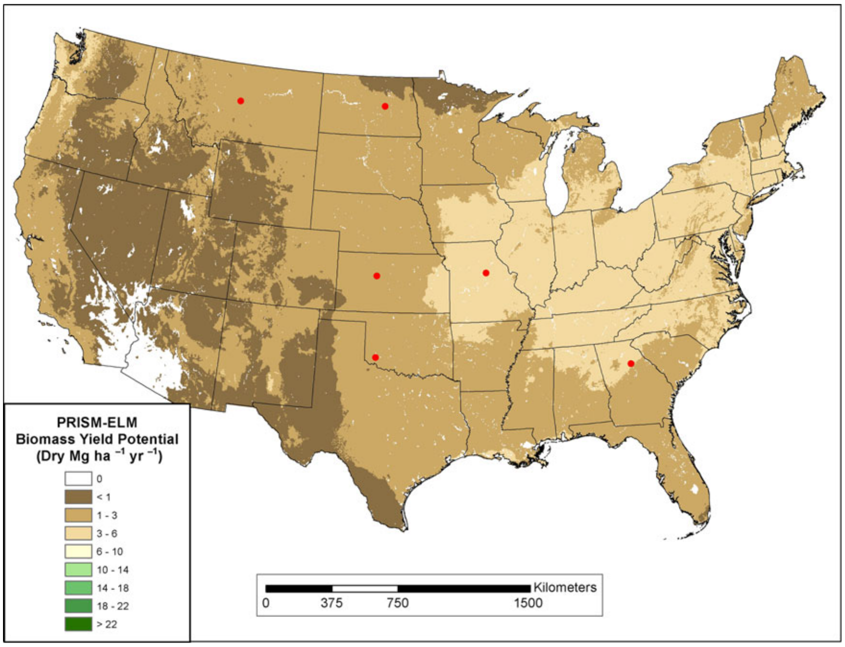

Fig. 9 Biomass yield potential of mixed grasses in the Conservation Reserve Program lands for the United States generated using the PRISM-ELM model and based in part on Regional Feedstock Partnership Field Trials (red dots).

Of course, the value of a ton of switchgrass will remain the key driver for feasibility for marginal land use and fertilization inputs (Fike *et al.*, 2017).

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 published research. The multiple years encompassed by this work also show changes in yield and N utilization that would not have been observable with shorter-term research. Switchgrass response to N is highly variable, but early yields (first 1–3 years) are likely to increase with added N when initial N fertility is low, as was suggested by this study. Our data also indicate that with soils of even moderate fertility, it may take several years of harvesting to reach a point at which N applications are beneficial or economical.

Miscanthus

Our results indicate that yields can be achieved and sustained at or above 15 Mg ha^{-1} across most years, locations, and fertilizer treatments, and that certain conditions can allow plants to substantially outperform this baseline standard. For example, after the third harvest, plots in IL and NJ responded to moderate fertilization to produce yields greater than 25 Mg ha^{-1}. From these data, we can conclude that a moderate fertilization treatment should be sufficient to augment yield in most locations and years, and that any additional fertilizer would be unnecessary, not cost-effective, and potentially harmful to the surrounding environment as nitrous oxide gas or nitrate leaching (Behnke *et al.*, 2012; Davis *et al.*, 2014). Furthermore, it appears that any amount of nitrogen will be unnecessary in many locations, at least within the first four growing seasons.

Winterkill occurred in the Illinois and Indiana first-year (2008) plantings and can be a concern when planting *M.* × *g.* in northern locations. It can be speculated that the late fall 2008 warm, wet conditions that were immediately followed by a great temperature drop were the possible cause. Additionally, rhizome freezing death has been reported by Lewandowski *et al.* (2000) in a study that found 50% of *M.* × *g.* rhizomes were killed at −3.4 °C. Also, first-year *M.* × *g.* plantings commonly remain green and actively growing longer into the autumn than plants in subsequent growing seasons, making autumn freezes a concern (Author observation). The later growth of first-year plants can possibly be attributed to ground that remains warmer in first-year plantings due to the lack of shade and layer of insulating straw that are found in older plantings.

When entered into a PRISM-ELM model, our data indicated that much of the Eastern United States is suitable for sustained Miscanthus yields of 18 Mg ha^{-1} or greater. These variations are primarily attributed to weather and site differences, but have not been substantial across this study. The low Miscanthus productivity in the southeast indicated by the PRISM-ELM model was also found by Fedenko *et al.* (2013) and Kiniry *et al.* (2013). In summary, our results suggest that Miscanthus can be a viable energy crop in an expanded region across many portions of the central-eastern United States.

Sorghum

Sorghum can produce high biomass yields on an annual basis across a wide range of the country, but producers and processors must recognize that yield variation due to environmental conditions is real and will affect biomass yields. When yield stability, production season, and the economics of production are considered, the best locales for the production of biomass sorghum appear to be in the southeastern United States from East Texas to the Atlantic Coast. Ultimately, biomass production of any type for bioenergy conversion will be determined by the profitability of the crop relative to other crop production options.

This modeling effort identifies where energy sorghum will have the highest yield, but yield *per se* does not mean that energy sorghum will be grown. Within regions, other factors such as existing cropping systems, infrastructure, and economics will strongly influence where the crops are produced. While the model does account for long-term moisture patterns in the form of an average, it does not reflect the stability of yield from year to year. For insight into this variation, Gill *et al.* (2014) clearly demonstrated greater variability in the drier regions, and increased variability in production increases risk in biomass supply to processing facility. These factors must be considered when evaluating yield production maps for any of the bioenergy crops.

Energycane

Energycane can produce MDMY of 23–25 Mg ha^{-1} $year^{-1}$ at the most northern locations (33° N latitude) and in excess of 37 dry Mg ha^{-1} yr^{-1} reliably at the Gulf Coast locations. As energycane is tropical in origin, it does not undergo fall senescence-like Miscanthus and lowland switchgrass. A freezing event (−6 °C) traps nutrients in the above-ground biomass; many of these nutrients are removed at harvest. At the northerly locations, energycane stem moisture concentration was ~710 g kg^{-1} before a killing frost, but increased to about 790 g kg^{-1} after freezing temperatures (data not shown). When a killing frost is experienced, leaves are damaged, but the stem and roots remain alive and active. We suspect that osmotic tension and roots (protected from the cold temperatures by the insulating effects of the soil) continue to push water to the aerial stem of the plant. Dead leaves, failing transpiration, cause stem moisture to increase after the freeze events. Infrastructure and equipment to handle this type of heavy wet biomass can be found in the sugarcane growing areas, but not at the northern locations.

At the more northerly locations, extremely cold winters limited energycane production. However, these locations allowed the breeders at the Sugarcane Research Unit to differentiate between lines that were more cold-hardy. In spite of being located within existing sugarcane production regions, most disease and insect pressure was negligible, with the exception of the presence of sugarcane borer (*Diatraea saccharalis*) and Mexican rice borer (*Eoreuma loftini*) at Beaumont. Sugarcane aphid (*Melanaphis sacchari*) was noted at several locations beginning in 2013, including Mississippi State, but they infested sweet sorghum more heavily than energycane.

While concentration is not as great as sugarcane, energycane stems contain substantial amounts of sugar (especially the pithy type, Ho72-114) that can be exploited through extraction (pressing) or via in situ fermentation. °Brix varies greatly due to location and environment within location. The only factor consistent for °Brix was Ho06-9001 and Ho06-9002 (woody types) provided less sap with lower °Brix than the other energycane types.

Conservation Reserve Program (CRP) Grassland

Conservation Reserve Program lands may represent an important resource for producing cellulosic bioenergy feedstock without competing for land with food, feed, and fiber production. Our long-term field study during 2008–2013 indicates that the annual biomass yield was 2.82 Mg ha^{-1} for warm-season mixture CRP land and 5.10 Mg ha^{-1} for cool-season mixture CRP land under best management practices (Anderson *et al.*, 2016). Nitrogen fertilization is the key agronomic management factor determining biomass yield on CRP land, but applications of 112 kg N ha^{-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).

By far, the greatest impacts on seasonal biomass production and changes in vegetation composition were due to location-specific precipitation. Except for the KS site, these yields were approximately three times higher than those projected in the PRISM-ELM model map, but align fairly closely with the estimates from the Billion Ton Update (United States Department of Energy, 2011). 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

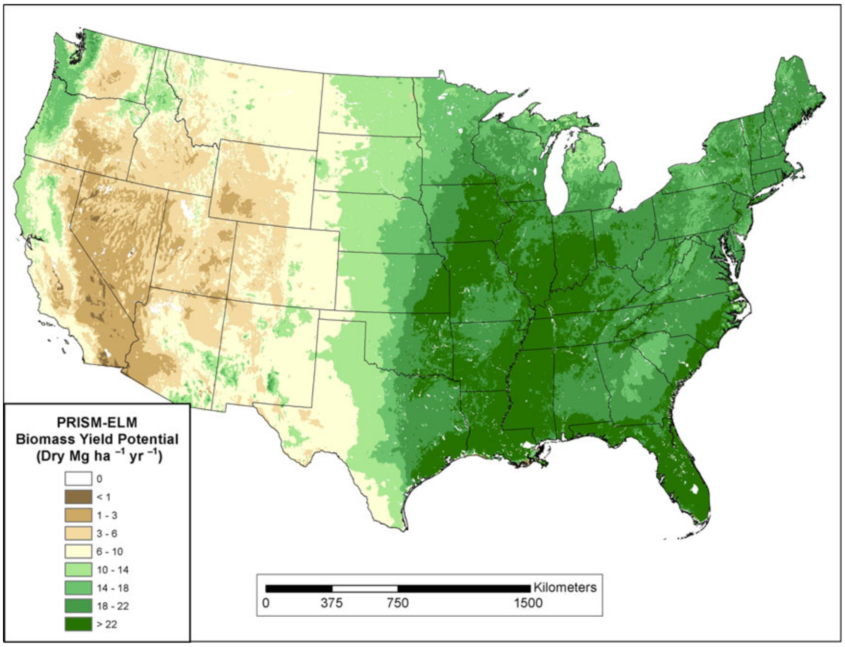

Fig. 10 Maximum average annual yield potential of herbaceous feedstocks (switchgrass, Miscanthus, sorghum, energycane, and Conservation Reserve Program mixtures) across the continental United States. Yield potential shown on this map is that of the highest of all species evaluated at a given location in the United States. This map was generated using the PRISM-ELM model and is based in part on data from Feedstock Partnership Field Trials.

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 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).

A considerable amount of land in the United States is under CRP contract, but this number is decreasing as farmers respond to higher price signals in grain markets. Finding a profitable production system for this land that would continue to provide the economic services proposed in the program would not only feed an emerging cellulosic biofuel industry, but also protect environmentally sensitive land and improve soil and water quality. 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.

Conclusion

Understanding the agronomic and economic perspectives of key feedstock species will be critical, making long-term farm-scale research (similar to the studies conducted under the Feedstock Partnership) an imperative moving ahead. Based on nonirrigated trials of these herbaceous species and CRP mixtures, the eastern half of the United States (basically east of the 100th meridian) and isolated locations west of this area are capable of producing significant biomass for a national bioeconomy utilizing at least one of these species (Fig. 10). The rapid reduction in yields west of the 100° W meridian correlates directly with the reduction in annual rainfall.

The work of the Feedstock Partnership expands our previous understanding of the bioenergy potential of switchgrass, Miscanthus, sorghum, energycane, and CRP mixtures. Previous knowledge was based primarily on small-scale and short-term studies that lacked real-world applicability. Results from 5 to 7 years of research across a wide variety of locations indicate where each of these species will perform best, aiding in decisions about feedstock selection. For example, Miscanthus and energycane attained the greatest yields, but other species may be preferable in locations where Miscanthus and energycane were not tested or were less successful, such as colder northern sites. The study also revealed that in some instances nitrogen fertilizer increased yield of biomass feedstocks to which it was applied, especially where soil N was naturally low prior to application, but it was not generally beneficial to apply it at the highest rate. Farmers can reduce production expenses and decrease environmental risks associated with over-application of N by tailoring their N application rates according to these results and their specific situation. Several of the feedstocks were difficult to establish due to mortality and weed problems. Research on improving establishment rates is needed, including research to identify and label effective herbicides for each feedstock. Furthermore, the work of the Feedstock Partnership has provided decision makers at all levels with updated, real-world data that could improve adoption and management of perennial bioenergy cropping systems. The raw data provided with this report allow for the possibility of further analysis and deeper investigation.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Dry biomass production of switchgrass at six locations that were part of the US Department of Energy/Sun Grant Initiative Regional Feedstock Partnership.

Table S2. Dry biomass production of *Miscanthus x giganteus* 'Illinois' at five locations that were part of the US Department of Energy/Sun Grant Initiative Regional Feedstock Partnership..

Table S3. Dry biomass production of six sorghum genotypes (five in 2008) at seven locations that were part of the US Department of Energy/Sun Grant Initiative Regional Feedstock Partnership.

Table S4. Dry biomass production of five energycane genotypes at eight locations that were part of the US Department of Energy/Sun Grant Initiative Regional Feedstock Partnership.

Table S5. Dry biomass production of warm- or cool-season grass mixtures on Conservation Reserve Program land at six locations that were part of the US Department of Energy/Sun Grant Initiative Regional Feedstock Partnership.