Poplar and shrub willow energy crops in the United States: field trial results from the multiyear regional feedstock partnership and yield potential maps based on the PRISM-ELM model

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Abstract

To increase the understanding of poplar and willow perennial woody crops and facilitate their deployment for the production of biofuels, bioproducts, and bioenergy, there is a need for broadscale yield maps. For national analysis of woody and herbaceous crops production potential, biomass feedstock yield maps should be developed using a common framework. This study developed willow and poplar potential yield maps by combining data from a network of willow and poplar field trials and the modeling power of PRISM-ELM. Yields of the top three willow cultivars across 17 sites ranged from 3.60 to 14.6 Mg ha\(^{-1}\) yr\(^{-1}\) dry weight, while the yields from 17 poplar trials ranged from 7.5 to 15.2 Mg ha\(^{-1}\) yr\(^{-1}\). Relationships between the environmental suitability estimates from the PRISM-ELM model and results from field trials had an \(R^2\) of 0.60 for poplar and 0.81 for willow. The resulting potential yield maps reflected the range of poplar and willow yields that have been reported in the literature. Poplar covered a larger geographic range than willow, which likely reflects the poplar breeding efforts that have occurred for many more decades using genotypes from a broader range of environments than willow. While the field trial data sets used to develop these models represent the most complete information at the time, there is a need to expand and improve the model by monitoring trials over multiple cutting cycles and across a broader range of environmental gradients. Despite some limitations, the results of these models represent a dramatic improvement in projections of potential yield of poplar and willow crops across the United States.

Keywords: Populus, Salix, short cutting cycle intensive culture, short-rotation woody crops

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Introduction

Efforts to develop perennial woody crops for the production of biomass have occurred over the past few decades as interest in the production of biofuels, bioenergy, and bioproducts has grown. In addition to biomass as a feedstock for renewable energy, these systems have the potential to generate multiple rural development and environmental benefits (Borjesson, 1999; Volk et al., 2004; Rowe et al., 2009). Studies in the northeast United States indicate that these systems have the potential to generate 45 to 65 direct and indirect jobs in rural areas for every 4,000 ha planted (Swenson, 2010; Swenson et al., 2015), have a low carbon footprint (Djomo et al., 2011; Caputo et al., 2014), enhance biodiversity across the landscape (Dhondt et al., 2007; Campbell et al., 2012; Tumminello et al., 2015), reduce soil erosion potential compared to annual crops, and protect water quality (Bressler et al., 2017).

The two main woody crops that have been bred and selected for commercial bioenergy production in the United States are shrub willow and eastern cottonwood, with its intra- and interspecific crosses within the genus Populus, generally known as hybrid poplars. Initial trials with shrub willow 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). Today approximately 500 ha of willow (Volk et al., 2016) and 120 ha of hybrid poplar as bioenergy crops are in commercial production in the United States. Willow shrubs (Salix spp.) have several characteristics that make them an ideal feedstock for biofuels, bioproducts, and bioenergy: high yields that can be sustained in three- to four-year cutting cycles, ease of propagation from dormant hardwood cuttings, a broad, underutilized genetic base, ease of breeding for several traits, ability to resprout after multiple harvests, and chemical composition and energy content similar to other northern hardwood species. Poplar domestication started in the lower Mississippi River Valley in the 1960s when the US Forest Service launched a program for Populus deltoides (Cooper, 1980). Later, the US Forest Service and the University of Minnesota developed the P. × canadensis taxon for the north central region, while the University of Washington began hybridization of the P. × euramerica taxon for the northwest during the 1970s (Heilman & Stettler, 1985; Riemenschneider et al., 2001). Poplar breeding programs were initially selecting cultivars for the pulp and paper and veneer industries, then were later reinvigorated by the renewable fuels market (Ribe 1974, Pontailler et al., 1999). Many of the same advantages conferred by willow for coppice biomass production also apply to hybrid poplar. One difference is how the two crops resprout after harvesting. Coppice production in poplar concentrates the biomass into a single dominant stem that, while creating harvesting challenges, may also result in a lower bark-to-wood ratio than willow, which produces a large number of smaller diameter stems after each harvest.

In order to expand the deployment and use of woody crops, there is a need for information on potential yields for different part of the United States. Actual yield data for willow and hybrid poplar have been limited to research plots that are geographically scattered and represent the growth potential on relatively small areas. These data are invaluable, but are limited by the small number of potential environments represented, inconsistency in the trial design and crop management (i.e., variations in planting density, planting stock, cutting cycle length, amount and frequency of nutrient amendments), and limitations in the length of monitoring. The latter issue is especially challenging for woody crops that can require up to 12 years for their first cutting cycle, which is the case for single-stem hybrid poplar plantings that often do not reach steady-state growth rates for many years. Willow and poplar coppice systems can reach their first harvest 2 to 4 years after planting, but their effective lifespan can be seven or more harvest cutting cycles. A single planting of willow can be in the ground for 25 years or more, experiencing a range of weather conditions and changes in management. Shorter-term academic research funding cycles often do not allow the monitoring of consistently managed trials across a range of sites and over longer periods of time. As a result, yield predictions across the United States that are done using a consistent modeling framework are lacking and interpolation of results from field trials has serious limitations.

National assessments of the biomass production potential in the United States were completed in 2005 (Perluck et al., 2005) and 2011 (U.S. Department of Energy, 2011). Both baseline and future yield estimates for energy crops for the 2011 Billion Ton Update report (U.S. Department of Energy, 2011) were based on expert input during a workshop (Ovard et al., 2009). At this event, invited experts provided input on currently achievable and projected yields for broad land resource regions that were adapted from USDA NRCS (Natural Resource Conservation Service). These estimates were based on the best available, but very limited, field-based data at the time and expert judgment. The land resource regions used each covered multiple states so spatial resolution was very limited. These broad yield estimates were used as input to the POLYSYS (Policy Analysis System) model to predict the production potential of these crops across the United States (U.S. Department of Energy, 2011). The POLYSYS model allocates available agricultural land among different uses based on the
maximization of expected returns using production and inputs and prices from various data based (De La Torre Ugarte & Ray, 2000). While the yield estimates used were the best available at the time, they had serious limitations in terms of both the field data supporting them and the spatial resolution.

There have been efforts to develop different predictive yield models across broad regions for willow and poplar over the past several years. Process-based models including BioCrop (Wang et al., 2015), 3PG (Amichev et al., 2011), and ForestGrowth-SRC (Tallis et al., 2013) have been developed for willow, and 3PG has also been calibrated for hybrid poplar in North America (Amichev et al., 2011). Other approaches have been developed to model regional willow yields in Europe (Lindroth & Bath, 1999; Aylott et al., 2008; Mola-Yudego & Aronsson, 2008; Mola-Yudego, 2010). These models are based on an understanding of the biological and biophysical mechanisms and processes that contribute to growth and yield and provide opportunities to improve our understanding of these dynamics. The drawbacks of these models are their complexity and the amount of environmental and crop physiology information that is required. For example, the BioCrop model developed for willow requires hourly weather data, soils data across 10 different layers, and a broad range of information on morphological and physiological characteristics. Empirical models are often easier to use, but yield data are often insufficient to drive them, and they do not provide as many insights into factors that are controlling yields across genotypes and sites.

A limitation for any yield prediction model that has been developed for woody crops is the small number of sites with good yield information from trials that have been managed in a consistent manner. One of the objectives of the Sun Grant Regional Feedstock Partnership (Owens et al., 2016) was to develop yield predictions of multiple herbaceous and woody perennial energy crops across the United States based on the network of field sites that had been established. Projecting dedicated energy crop yields across the United States with improved spatial resolution, compared to the 2011 Billion Ton Update report, required a consistent modeling framework for the range of herbaceous and woody perennial energy crops across the United States based on the network of field sites that had been established. Projecting dedicated energy crop yields across the United States with improved spatial resolution, compared to the 2011 Billion Ton Update report, required a consistent modeling framework for the range of herbaceous (Lee et al., 2017) and woody crops to minimize differences in the ways in that modeled crop yields are projected based on factors such as climate, soils, and genetics. The output from the yield modeling for each of the bioenergy crops was then used as input for POLYSYS for the third Billion Ton report (U.S. Department of Energy, 2016). POLYSYS had energy crops compete against one another and traditional agricultural crops to select the land use for a given region, a consistent modeling framework across all the crops was important. Output from POLYSYS at different price points was used to predict the production potential of these crops across the United States.

There have been initiatives to develop a common process-based model framework that can be applied to a range of different crops. For example, a common process-based model approach has been developed using the BioCrop mechanistic modeling framework for willow (Wang et al., 2015; Larsen et al., 2016), switchgrass, and Miscanthus (Miguez et al., 2009, 2012), but as noted above, these models require large amounts of data input and this information was not collected as part of the Sun Grant Feedstock Regional Feedstock Partnership program.

The model selected for yield modeling of dedicated energy crops was the PRISM-ELM (Parameter-elevation Regressions on Independent Slopes Model-Environmental Limitation Model). It is a statistical–mechanistic model that encompasses both empirical and mechanistic techniques to develop projections of potential yield based on climate and soil parameters. PRISM-ELM 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 (Daly et al., 2018).

The objectives for this work were to provide the yield and site data for willow and poplar across a range of trials as input to develop potential yield maps for willow and hybrid poplar perennial energy crops using the PRISM-ELM model.

Materials and methods

Willow trials

A network of 28 willow trials established between 1997 and 2009 were originally selected for this study. After a review of the data, four trials established before 1997 were excluded because they only contained unimproved cultivars that are no longer representative of the yield potential of willow. Trials planted between 1997 and 2004 included plant material from University of Toronto and the Ontario Ministry of Natural Resources and some material from wild collections from the northeast and Midwest United States (Smart et al., 2005). Trials planted starting in 2005 incorporated new cultivars that were produced from breeding in the late-1990s (Serapiglia et al., 2013). At locations where multiple trials were established in different years as new cultivars were developed, the most recently planted trial with harvest data was used to represent yield potential. This eliminated four additional trials from the original data set. During the initial modeling, three trials showed as outliers and, after discussion with experts familiar with these trials, the locations were removed because of
different site conditions (Fredonia, NY), crop management (Delhi, NY), or excessive deer and weed pressure (Potsdam, NY). The final set of data used to develop the model and regional yield predictions included 17 yield trials in eight different states (Table 1).

An advantage of this suite of trials is that they had similar experimental designs, plot layouts, and crop management. Each trial had three or four replications in a randomized complete block design. The only treatment in each of the trials was cultivar, and there were 6–30 varieties in each trial. Trials were all hand planted with 25-cm-long dormant willow cuttings in the spring. All plots contained three double-rows and used the same spacing, 1.50 m between double-rows, 0.76 m within a double-row, and 0.61 m between plants within a row (Fig. 1). There were 13 to 25 willows planted in each row resulting in the length of each plot varying from 7.92 to 15.24 m. The measurement plot for all trials included 10 to 18 plants in the center double-row, depending on the trial. All plants were coppiced after the first growing season. At the beginning of the second growing season, 100 kg N ha$^{-1}$ was applied to all trials except the yield trials at Arlington, WI, Brimley, MI, Escanaba, MI, and Skandia, MI. Weed control was accomplished using broad-spectrum contact herbicides and tillage prior to planting, selective pre-emergent herbicides immediately after planting, and selective postemergent herbicides and mechanical weed control in the first year or two after establishment. Trials were harvested either by hand or mechanically after leaf fall and weighed in the field 3 years after coppicing (4 years after establishment). A subsample of harvested material was collected, weighed soon after harvest, and dried to a constant weight to determine moisture content. Yields are reported as dry Mg ha$^{-1}$ yr$^{-1}$ across all the trials. Four trials were harvested after a second, 3-year cutting cycle, and one trial was harvested for each of three, 3-year cutting cycles.

Since an annualized estimate of yield covering a 30-year time frame was required for each site as input to the PRISM-ELM model, two decisions had to be made on how to calculate this number. The first was the number of varieties to include in yield calculations, since trials included between 6 and 30 cultivars. The second decision was how to model the mean annual yield from second through seventh cutting cycles based on first cutting cycle yields. While it could be argued that the willow yield potential at any particular site might best be represented by the yield of the best cultivar, this would not be representative of the potential of the system if it was deployed across the landscape. Current recommendations for large-scale plantings of willow

Table 1 Information on the shrub willow trials used to develop a national yield map using the PRISM-EM model.

| Trial name and planting date | State | No. varieties | Cutting cycle length (years), number of rotations with yield data |
|-----------------------------|-------|---------------|---------------------------------------------------------------|
| Burlington 1997             | VT    | 6             | 3, 1                                                          |
| Canastota 1998              | NY    | 13            | 3, 3                                                          |
| Peter’s Tract 1998          | DE    | 12            | 3, 1                                                          |
| Wolcott 1998                | NY    | 11            | 3, 1                                                          |
| Arlington 1999              | WI    | 10            | 3, 1                                                          |
| Queenstown 2001             | MD    | 15            | 3, 1                                                          |
| Lansing 2002                | MI    | 12            | 3, 1                                                          |
| Belleville 2005 (SG*)       | NY    | 18            | 3, 2                                                          |
| Tully 2005 (SG)             | NY    | 18            | 3, 2                                                          |
| Constableville              | NY    | 30            | 3, 2                                                          |
| 2006 (SG)                   |       |               |                                                               |
| Waseca 2006                 | MN    | 26            | 3, 2                                                          |
| Middlebury 2007 (SG)        | NY    | 30            | 3, 1                                                          |
| Escanaba 2008 (SG)          | MI    | 26            | 3, 1                                                          |
| Big Flats 2008 (SG)         | NY    | 8             | 3, 1                                                          |
| Brimley 2009 (SG)           | MI    | 20            | 3, 1                                                          |
| Skandia 2009 (SG)           | MI    | 20            | 3, 1                                                          |
| Storrs 2009 (SG)            | CT    | 20            | 3, 1                                                          |

*SG indicates trials that were supported by the Sun Grant Regional Feedstock Partnership.

Fig. 1 Example of an individual willow plot for one cultivar in a yield trial. A typical plot was three double-rows wide and 13 plants long. The three double-row layout and the plant spacing were common across all of the trials in this study, but the number of plants in a row and in a measurement plot varied among the trials. The minimum number of plants in a measurement plot in any of the trials was 10.
biomass crops are to deploy multiple, genetically diverse cultivars in order to hedge against the possibility of pest or disease susceptibility and due to our lack of complete understanding of genotype-by-environment (G × E) interactions (Heavey & Volk, 2016). To be consistent across sites and still capture the variation that occurs among cultivars and across sites, the data from the top three cultivars at each site were chosen as being most representative of the yield potential.

The coppice management system for willow biomass crops created another challenge for estimating yield potential across this range of sites. After each 3-year cutting cycle, the willows resprout and grow for another cutting cycle. Seven three-year cutting cycles are the framework that has been used for modeling willow biomass crops for economic and life cycle analysis studies (Buchholz & Volk, 2013; Caputo et al., 2014). From the set of sites used for model development, there were four trials with data for more than one cutting cycle: Belleville, Constableville, Tully, and Waseca with two cutting cycles, and one site (Canastota) with three cutting cycles. One other trial planted earlier at the Tully site, but excluded from the PRISM-ELM modeling data set because there was a later planted trial, had completed four cutting cycles. Data from the multiple cutting cycles were assembled, and the mean annual yield of the top three cultivars in each cutting cycle for each trial was summarized. Using the first cutting cycle as the base, the percent change in yield for the top three cultivars at each site for second, third, and fourth cutting cycles was calculated. Since none of the trials in this data set had been harvested for the fifth through seventh cutting cycle, yields for these rotations were assumed to be the same as the projected yield from the fourth cutting cycle. For the trials that only had data from the first cutting cycle, yields in subsequent cutting cycles were projected using the average percent increases that were measured at other sites. The final yield potential of each site (Mg ha⁻¹ yr⁻¹) was based on the yield of the top three cultivars at each site over seven-three-year cutting cycles.

**Hybrid poplar trials**

The initial data set for hybrid poplar included 97 genotype/site combinations ranging from large commercial yield blocks using proven varieties in the Pacific Northwest and Mid-South to new hybrids in yield blocks embedded in commercial acreage in the north central region as well as cultivar tests on sites in the southeast region. Some sites and genotypes were eliminated from the database due to issues with uncertain stand history or where irrigation was used. Due to the wide geographic range represented by the trials, the set of genotypes encompassed by the trials were region specific. Thus, yield data were representative of a collection of proven high-yielding, disease-resistant, near-commercial genotypes appropriate for each region. While there were multiple genotype/site combinations, the decision was made to represent the potential yield at the site level using the three highest-yielding genotypes.

The 17 hybrid poplar field trials used to develop the model were located in four major regions: the Pacific Northwest, the Midwest, South/Mid-South alluvial, and the southeastern upland and included a mixture of commercial site and research trial locations (Table 2). The sites included different cultivars, spacings, and ages, which required some additional effort so that a representative mean annual increment required for model development could be calculated. In most cases, survival, height, and diameter data were collected annually and growth curves over the complete cutting cycle were developed. In cases where the stand had not reached full cutting cycle age, we estimated the final yield based on the steady-state growth rate after full canopy closure has occurred and extended that growth rate to full cutting cycle (Owens et al., 2017). Pacific Northwest information was based on GreenWood Resources’ site adaptability trials of a consistent set of clones replicated across three locations in the in the lower Columbia River floodplain, Puget Sound basin, and the Coast Range foothills. The adaptability trials were designed as randomized block experiments with four replications and four-tree row or square plots. Yields from commercial plantations along the lower Columbia floodplain were compared to modeled yields for this region.

Data from Midwest plots were collected from a network of yield trials with replicated cultivar plots maintained by the University of Minnesota and Michigan State University. University of Minnesota trials consisted of replicated cultivar plots containing 49 trees (7 × 7 plots) with the inner nine trees serving as the measurement plot. All Michigan State trials were composed of replicated 64-tree plots with measurements taken on the inner 16 trees. Annual standing biomass was estimated using an allometric equation developed by Wang & MacFarlane (2012). In most cases, data were collected annually on these sites and growth curves over the complete cutting cycle were developed. Where the stand had not reached full cutting cycle age, the final yield was estimated based on the steady-state growth rate after full canopy closure from the other sites.

South/Mid-South alluvial sites were planted in commercial programs operated by MeadWestvaco in Kentucky and Illinois located primarily along the Mississippi River Valley. Commercial-scale poplar plantations established through MeadWestvaco’s program
provided an opportunity to measure existing stands that were at or near maturity. A total of 302 measurement plots in 30 genotype/site combinations were measured and included in the dataset. The average spacing in these stands was 686 trees ha\(^{-1}\), with age at the time of measurement ranging from 5 to 11 years. Where stands were <9 years old, growth was estimated at 9 years by developing a regression equation of total stand biomass on age for the entire dataset and estimating the stand biomass for younger stands by a simple ratio of the expected stand biomass (average estimated by the regression equation) to the actual biomass at the current stand age (Owens et al., 2017).

Data for the southeast uplands were based on genotype trials recently established by ArborGen on a variety of sites with ages ranging from 3 to 9 years with most sites falling near the younger end of the age range at the time of this project. These were replicated cultivar trials established at different spacings. The sites contained at a minimum six single-tree plots replicated four times, or two-tree plots replicated at least four times. For the one-nine-year-old trial, the mean height and diameter of all genotypes in the trial were used as a conservative estimate of closed-canopy long-term yield. In light of the fact that the available field study dataset consisted primarily of younger stands, we attempted to find long-term production datasets that would allow us to put early cutting cycle performance of genotypes in younger genotype tests into a context of established long-term growth from other studies. Krinard (1988) and GreenWood Resources data were used to develop reference growth curves to predict yield at final cutting cycle age. Details of the models developed and used to estimate yield are available in Owens et al. (2017).

### PRISM-ELM model

The PRISM-ELM was developed to answer the basic question: In the absence of detailed, quantitative information on the environmental tolerances of a given crop, how do climate and soil characteristics affect the spatial suitability and long-term production patterns of a given crop? The model employs a limiting factor approach, where the final environmental suitability index (ESI; 0–100\%) is the lowest suitability index resulting from sub-models that simulate water balance; winter low-temperature response; summer high-temperature response; and soil pH, salinity, and drainage. Climate data for the model come from the PRISM AN81d data set (PRISM Climate Group, 2015), and soils data are from USDA NRCS genera soil map coverage (USDA NRCS, n.d.). The model was parameterized and validated using grain yield data for winter wheat and maize (Daly et al., 2018). Model settings for these well-known crops were

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**Table 2** Network of poplar trials and yield data used in the PRISM-ELM model to create a national yield map.

| Trial               | Establishment date | Location               | Number of varieties | Spacing (m) | Cutting cycle length (years), number of cutting cycles with yield data | MAI (Dry Mg ha\(^{-1}\) yr\(^{-1}\)) |
|---------------------|--------------------|------------------------|---------------------|-------------|--------------------------------------------------------------------|--------------------------------------|
| Angelo*             | 1999               | Alexander County, IL    | 4                   | 3.66 × 3.66 | 8, 1                                                               | 15.2                                 |
| Bellville           | 2010               | Evans County, GA        | 7                   | 2.44 × 2.44 | 7, 1                                                               | 13.5                                 |
| Eastover            | 2008               | Eastover, South Carolina| 243                 | 3.05 × 1.22 | 7, 1                                                               | 12.5                                 |
| Floyd               | 2003               | Floyd County, GA        | 120                 | 3.66 × 2.44 | 9, 1                                                               | 12.8                                 |
| Hansen              | 2006               | Todd County, MN         | 22                  | 3.05 × 1.83 | 10, 1                                                              | 8.2                                  |
| Hemming             | 2005               | Todd County, MN         | 33                  | 3.05 × 1.83 | 10, 1                                                              | 10.5                                 |
| Island 3            | 2005               | Carlisle County, KY     | 7                   | 3.66 × 3.66 | 6, 1                                                               | 10.4                                 |
| Joppru              | 1996               | Pennington County, MN   | 8                   | 2.44 × 2.44 | 13, 1                                                              | 10.1                                 |
| Kniels              | 1999               | Ottertail County, MN    | 4                   | 3.05 × 1.83 | 10, 1                                                              | 7.5                                  |
| LEA Grand Rapids    | 2007               | Itasca County, MN       | 9                   | 2.44 × 2.44 | 10, 1                                                              | 11.1                                 |
| Peck                | 2005               | Lake County, TN         | 1                   | 3.66 × 3.66 | 6, 1                                                               | 12.4                                 |
| Puyallup            | 2005               | Pierce County, WA       | 67                  | 1.83 × 1.83 | 5, 1                                                               | 9.5                                  |
| Schultz             | 2007               | Todd County, MN         | 12                  | 3.05 × 3.05 | 10, 1                                                              | 8.0                                  |
| Sebeka              | 1996               | Wadena County, MN       | 1                   | 2.44 × 2.44 | 10, 1                                                              | 7.6                                  |
| Wise                | 2003               | Mississippi County, MO  | 1                   | 3.66 × 3.66 | 8, 1                                                               | 14.0                                 |
| Woelfel             | 2001               | Todd County, MN         | 4                   | 3.05 × 1.83 | 10, 1                                                              | 7.8                                  |
| Wooten Farm         | 2010               | Pitt County, NC         | 9                   | 3.05 × 1.22 | 7, 1                                                               | 10.6                                 |

*All sites except Angelo (measured at seven not 8 years) were measured at the projected rotation age, and yield was estimated based on allometric equations.*
then used as “anchor points” in setting parameters for a range of biomass crops for which less information on environmental tolerances was available. Data on specific energy crop tolerances available from the literature or from experts that participated in the process were incorporated. Once ESI maps were created, potential yield maps were derived using regression models of ESI and actual yields from the network of field trials available. This approach allows potential yields to be projected across the landscape based on climate and soils information and the relationship with measured or estimated yield at the network of sites. An important component of the modeling process was close interaction between energy crop specialists conducting the Sun Grant field trials and the PRISM-ELM modeling group. Details on the PRISM-ELM model and how it was applied to woody crops are provided in Daly et al. (2018).

Results

Regional yields from willow field trials and PRISM-ELM model

Mean annual yields from the first 3-year cutting cycles were calculated for the top cultivar, the top three cultivars, and the top five cultivars at each site (Fig. 2). There was more than a fourfold difference in the yield of the top cultivars across the sites, ranging from 3.83 Mg ha\(^{-1}\) yr\(^{-1}\) in Skandia to 16.0 Mg ha\(^{-1}\) yr\(^{-1}\) in Storrs. The annual yield values decreased from the top one to the top three cultivars at all the sites, illustrating the importance of including a mixture of cultivars for this modeling work. For the top three cultivars, the yield ranged from 3.60 Mg ha\(^{-1}\) yr\(^{-1}\) in Skandia to 14.6 Mg ha\(^{-1}\) yr\(^{-1}\) in Arlington. For the top five cultivars, yield ranged from 3.38 Mg ha\(^{-1}\) yr\(^{-1}\) in Skandia to 14.0 Mg ha\(^{-1}\) yr\(^{-1}\) in Middlebury. The difference in yield between the top cultivar and the top three cultivars across all the sites was 11.4%. The smallest difference in yield at an individual site was 1.2% at Waseca, and the largest was at Lansing (34.3%). The drop in yield from the top cultivar to the top three cultivars was lower (7.5%) for sites planted in 2005 and later, which included new genetic material from breeding efforts in NY, compared to pre-2005 trials (15.5%). The decrease in yield from the top cultivar to the top five cultivars was 17.8% across all the sites with the smallest change at Middlebury (3.1%) and the largest change at Lansing (44.8%). The change in yield from the top cultivar to the top three cultivars was smaller for trials planted with improved cultivars after 2005 (7.5%) compared to pre-2005 trials (15.5%), where unimproved cultivars were planted. The difference was larger for the change in yield from the top cultivar to the top five cultivars; the mean change was 25.4% in pre-2005 trials and 11.8% in post-2005 trials.

Changes in yield from the first to the second cutting cycle for the top three cultivars across the five sites where data were available ranged from an increase of 6.8% at Belleville to an increase of 20.1% at Constableville. Across the five sites, the mean increase was lower (7.5%) for sites planted in 2005 and later, which included new genetic material from breeding efforts in NY, compared to pre-2005 trials (15.5%). The decrease in yield from the top cultivar to the top five cultivars was 17.8% across all the sites with the smallest change at Middlebury (3.1%) and the largest change at Lansing (44.8%). The change in yield from the top cultivar to the top three cultivars was smaller for trials planted with improved cultivars after 2005 (7.5%) compared to pre-2005 trials (15.5%), where unimproved cultivars were planted. The difference was larger for the change in yield from the top cultivar to the top five cultivars; the mean change was 25.4% in pre-2005 trials and 11.8% in post-2005 trials.

Changes in yield from the first to the second cutting cycle for the top three cultivars across the five sites where data were available ranged from an increase of 6.8% at Belleville to an increase of 20.1% at Constableville. Across the five sites, the mean increase was

![Fig. 2](image-url) Annual yield (dry Mg ha\(^{-1}\) yr\(^{-1}\)) of the top one, three, and five cultivars from the 17 willow biomass crops trials that were used to develop the regional yield models. The location and date of planting are included in trial names on the x-axis.
13.7 ± 5.8%. Based on the available data, mean increases in yield for the subsequent cutting cycles were 13.7% (1st to 2nd cutting cycle), 19.8% (1st to 3rd cutting cycle), and 13.4% (1st to 4th through 7th cutting cycles).

The environmental factors from the PRISM-ELM that limited potential yield of willow across the United States were dominated by climate-related issues (Fig. 3). The southern part of the United States was limited by summer heat, largely because the breeding and selection efforts for willow in the United States have been focused on north temperate regions. Across much of the rest of the United States, the water balance is the primary factor that limits willow yield.

After adjusting for changes in yield over multiple cutting cycles, the projected yields across the 17 willow sites ranged from 7.76 Mg ha\(^{-1}\) yr\(^{-1}\) to 16.5 Mg ha\(^{-1}\) yr\(^{-1}\) (Fig. 4). The PRISM-ELM model projected ESI based on the final set of parameters ranged from 46.9% at Brimley to 80.0% at Arlington. A linear relationship between ESI and measured yield had a \(R^2\) of 0.5516 with all the sites included. One site in particular (Waseca, MN) impacted this regression and when the relationship was assessed without this site the \(R^2\) rose to 0.8069. The ESI map created from the PRISM-ELM model was translated into an US potential average annual yield map using the stronger relationship to provide a greater degree of confidence in the results. The main changes in the maps from the two relationships were that yields were lower than measured in northern regions when the lower \(R^2\) relationship was used and the stronger relationship better represented yields across the range of sites. This map represents average annual yield over seven-three-year rotations for willow.

The largest yields were estimated at 18–22 Mg ha\(^{-1}\) yr\(^{-1}\) in patches from the Midwest down toward the southeast region (Fig. 5). There were large areas across the Midwest into West Virginia, Pennsylvania, portions of New York, New England, and the mid-Atlantic region where yields were in the 14–18 Mg ha\(^{-1}\) yr\(^{-1}\) range. On the western, southeastern,
and northeastern edges of the projected areas for willow yields were in the 10–14 Mg ha\(^{-1}\) yr\(^{-1}\).

**Regional yields from poplar field trials and PRISM-ELM model**

Water balance in the PRISM-ELM model was the environmental factor that limited poplar yields across most of the country (Fig. 6). The areas limited by winter cold and summer heat were much smaller for poplar than for willow in part because there has been intentional breeding of poplar for a broader range of conditions.

After adjusting for factors related to age and spacing in the network of poplar trials, the average annual yield over an entire cutting cycle was 7.5 to 15.2 Mg ha\(^{-1}\) yr\(^{-1}\) (Fig. 7). The ESI values projected by the PRISM-ELM model ranged from 53.1% to 86.3%. The relationship between ESI and mean annual increment based on the data from the network of yield trials had an \(R^2\) of 0.60.

The projection of yield for poplar across the United States showed that yields of poplar >10 Mg ha\(^{-1}\) yr\(^{-1}\) were possible across much of the eastern United States and on the west side of the Cascade mountains in the Pacific Northwest’s lower Columbia River valley, Willamette Valley, and the Puget Sound basin on the (Fig. 8). In the East, yields above 10 Mg ha\(^{-1}\) yr\(^{-1}\) were projected from Florida to Maine and from southern Wisconsin to southern Texas, demonstrating hybrid poplar’ adaptability to a broad geographic range of conditions. The greatest projected yields were in the 14–18 Mg ha\(^{-1}\) yr\(^{-1}\) range and were found in the central Midwest region with smaller patches in the Plains, Appalachia, and the northeast.

Combining the results from the willow and poplar maps provides an indication of the yield potential for woody crops across the entire United States (Fig. 9). Woody crops yields of >10 Mg ha\(^{-1}\) yr\(^{-1}\) are possible across the eastern half of the United States and in pockets in the Pacific Northwest and the Southwest. This highest potential yields are in the Midwest United States, in areas in the northeast and pockets in the southeast based on the results of this model. As noted above, there are regions of the country, such as the lower Columbia River Valley in the Pacific Northwest or isolated research trials in other areas, where there are some records of higher yields for either poplar or willow.

**Discussion**

The goal of using a common modeling framework (Daly et al., 2018) for these woody crops and a diversity of herbaceous crops (Lee et al., 2017) was important because one of the intended uses of the regional yield data was as input to the POLYSYS model. POLYSYS was used to develop estimates of future biomass production potential in the United States (U.S. Department
of Energy, 2016). Since a common modeling framework was implemented across the crops, the same soils and climatic data were used at a common resolution and there was consistency in how potential yield models were developed. Importantly, this minimized differences associated with how potential yield was predicted so different crops could be included in areas where production overlapped and the POLYSYS model could be used to determine which crops should be grown in certain regions of the country.

The willow yields projected by the PRISM-ELM model are within the range of values measured in North America. The highest estimated willow potential yields from PRISM-ELM were in the 18–22 Mg ha⁻¹ yr⁻¹ range. Measurements of willow yields in trials of improved cultivars in central New York have reached 27 Mg ha⁻¹ yr⁻¹ with irrigation and fertilization (Adegbidi et al., 2001), exceeded 24 Mg ha⁻¹ yr⁻¹ on fertilized sites in Quebec (Nissim et al., 2013), and maximum yield potential in Quebec has been predicted to be above 28 Mg ha⁻¹ yr⁻¹ (Fontana et al., 2016). Yields of the top three willow cultivars over two cutting cycles ranged from 10.3 to 14.2 Mg ha⁻¹ yr⁻¹. Across all the sites, the average yield over two cutting cycles was 11.7 Mg ha⁻¹ yr⁻¹. The estimates of potential yield from the PRISM-ELM model are well within the range of other measured and predicted yields.

The potential yield presented in the willow map is based on field measurements across a range of sites, but all of them were small research plots. Yields measured in research trials are often higher than what is recorded in large-scale commercial fields (Karp & Shield, 2008; Lobell et al., 2009), but at this point are the best data available to predict regional yields. The difference between research trials and commercial fields was not factored into the development of either the willow or poplar models. There is very little large-scale published production data currently available for willow or poplar.
biomass crops in the United States. Production reported from commercial-scale harvesting operations from two fields in New York ranged from 20 to 91 Mg ha\(^{-1}\) for material harvested from 4-year-old aboveground stems with an average moisture content of 44.4% (Eisenbies \textit{et al.}, 2014). This translates into 2.8 to 12.7 Mg ha\(^{-1}\) yr\(^{-1}\) of dry matter, which is at the low- to mid-range of yields from field trials. This study reported that losses at the time of harvesting ranged from 1.5 to 2.1 Mg ha\(^{-1}\) yr\(^{-1}\) of dry biomass or 0.4 to 0.5 Mg ha\(^{-1}\) yr\(^{-1}\). These fields were some of the first large-scale plantings of willow biomass in the region, so the establishment practices and crop management activities did not always follow best practices. In particular, there was poor weed management, which resulted in lower stand density in these fields and lower yields. Recently published data from poplar biomass crop harvested using commercial-scale equipment in the Pacific Northwest reported yields ranging from 11.9 to 18.1 Mg ha\(^{-1}\) of dry biomass (Eisenbies \textit{et al.}, 2017), which exceeded what the model predicted for this region. Part of this variation was due to differences in spacing and cultivars that were being tested, but the range of values matches well with the projected yield values for the Pacific Northwest region from the PRISM-ELM model. To improve the accuracy of these potential yield projections, there is a need for more large field scale data from poplar and willow biomass crops across a range of sites.

The poplar potential yield map was based on data from a mixture of small research trial plots and larger trials imbedded in commercial plantations, especially in the Midwest and southeast Alluvial region. Yield plots embedded in commercial plantations are more representative of commercial yields because management is similar to the surrounding commercial stand and any edge effects are eliminated. Modeled results from the Pacific Northwest are in agreement for the Coast Range foothills but are substantially lower than yields measured in production plantations along the lower Columbia River floodplain. Commercial production as measured in yields plots at the Lower Columbia River Farm has recently achieved production levels of up
The network of willow yield sites included in this modeling exercise was the most extensive and robust set at the time the model was constructed, but the range of environments and number of the sites were limited. Despite these limitations, this data set and the associated modeling is a significant step forward from previous projections of yield. Most of the trial sites were located in the northern half of the predicted willow range, with the sites in Maryland and Delaware being the furthest south. These sites did not include any of the improved cultivars from the willow breeding efforts that started in the late 1990s, so may not represent the current yield potential for these regions. There was a lack of trials located in the Midwest region where the greatest yields were predicted by the model. Future efforts should focus on including trials in predicted high potential yield areas and at sites that will extend the range of environments, so that the model can be developed across larger gradients, especially for water availability and temperature.

Existing willow cultivars in North America have been selected in a narrow range of environments in the northeast, which has resulted in a limited adaptation range for willow. The genotypes that were available to include in this network of trials were selected for breeding in southern Ontario in the early 1990s and in breeding programs located in central New York starting in the late 1990s (Smart et al., 2005). Most of the parental material used for breeding in North America is adapted to temperate areas of Europe and Asia and was not selected for lower latitudes in the southern United
States. There are species of willow adapted to these warmer climates that could be incorporated into breeding programs targeted at lower latitudinal climates (Stanton et al., 2014).

The poplar model included sites that covered a much broader gradient compared to willow and the relationship between ESI and measured yield was weaker for poplar ($R^2 = 0.60$ compared to 0.81 for willow). The limited number of data points across this broad gradient is clearly a limitation of this work, and the model could be improved by intentionally initiating trials in areas where there are gaps such as the Pacific Northwest, high-yielding areas of the Midwest, and the fringes of the projected 10 to 14 Mg ha$^{-1}$ yield range in the north and south. There is a broad range of genetic material that could be included in these trials because of the long history of hybrid poplar breeding, which started in North America in the early 1900s and has continued at different levels of intensity since that time (Stanton et al., 2010, 2014). This has generated a broader range of commercial genotypes adapted to a wide range of sites allowing the genus to produce good yields across large geographic ranges. The selection of the best genetic material in future trials based on information that is available is also important to improving the accuracy of this potential yield map.

A legitimate criticism of this methodology is that future growth patterns for these long-lived perennial crops are not well understood. Future growth may or may not continue at the current rate and growth curves may be affected by site conditions or future weather variations that may differ from the 30-year climate data set that was used in the model (1981–2010 mean precipitation and temperature). This issue is particularly true for the poplar projections in the southeast upland region. However, we had one site (Floyd, GA) where height growth patterns later in the cutting cycle substantiated our methodology. The average height of the ten tallest genotypes at the Floyd site was 17.7 m and 21.6 m at ages eight and nine, respectively,
approximately 90% of the modeled height. The question of future growth patterns can only be answered by measurements over a full cutting cycle of the existing Sun Grant network of trials and the establishment of new yield studies with new cultivars across the region.

The projection of willow yields over the 30-year time frame used in the model was based on the limited set of data over multiple rotations that were available at the time. In addition to the four trials in the data set that had been monitored for more than one cutting cycle, there were data from an older trial with unimproved cultivars over seven cutting cycles. These data were not included in the model because there was a more recent trial at this site (Tully 2005) and all but one of the cultivars in the trial were not improved and are no longer used. However, the yield pattern over the seven cutting cycles supports our approach to projecting yields into the future. The yield of a single cultivar (SV1) that is still commercially available had production in the 5th, 6th, and 7th cutting cycle was 162%, 125%, and 127% of the yield that was measured in the first cutting cycle (Volk, pers. comm). The yield in the seventh rotation for SV1 was $11.2 \pm 1.3\, \text{Mg ha}^{-1}\, \text{yr}^{-1}$. The yield of most other cultivars in this trial was also maintained, but their yields were much lower in the $4-8\, \text{Mg ha}^{-1}\, \text{yr}^{-1}$ and so are not as representative. For SV1, at this site, it is clear that yield is maintained over seven cutting cycles; however, the pattern of changes in yield over multiple cutting cycles may be different for improved cultivars that have been developed in North America and may vary across sites.

A limited amount of data is now available on how the yield of improved willow cultivars changes over time. Results from five trials in three different states show that for the top three cultivars, the change in yield from first to second cutting cycle ranged from a decrease of 8.2% to an increase of 18.0% (Sleight et al., 2015). This data set suggests that the change in yield from first to second cutting cycle is related to the change in yield of the first cutting cycle yields with lower initial yield generally having greater increase in yield in the second cutting cycle. Despite the difference in this pattern, the average yields

Fig. 9  Map showing the greatest potential biomass yield of woody crops (poplar or willow) across the United States.
across all five sites for the top three cultivars were 11.7 Mg ha\(^{-1}\) yr\(^{-1}\), which was in the mid-range of yield projected by the PRISM-ELM model. Collecting data from a range of trials across different sites over multiple rotations would increase the understanding of how willow yields change over multiple cutting cycles and could be used to improve the accuracy of future modeling.

Between 60 and 81% of the variation in the relationship between the predicted yield and measured yield was explained in the models. The large amount of unexplained variation is undoubtedly due to the vagaries of G × E interactions, pest damage, disease pressure, crop management, soil conditions, and weather. While there was some consistency in the top three cultivars in both the poplar and willow trials, it was not absolute, indicating the existence of G × E interactions, as has been previously reported (e.g., Fabio et al., 2017a,b). The decision to use the top three cultivars at each specific site was intended to capture the best yield potential at each site.

The yield of woody crops is typically averaged across multiple years. These long-term averages do not capture year-to-year abnormalities in weather conditions, such as late spring or early fall frosts, droughts, or precipitation concentrated in infrequent, intense events rather than more evenly distributed over the growing season. These year-by-year variations in weather are reflected in the yields that are measured every 3 years at the field sites, but are not directly associated with the long-term climate data that were used. For example, at the Middlebury site, annual growth data collected over two cutting cycles showed that a drought in 2012 reduced yield by about one-third in the second year of growth in the second cutting cycle compared to the second year of growth in the first cutting cycle when the general expectation would be that second rotation yields would be higher (Shi et al., 2014). The model did not capture this kind of year-to-year variation because annual yield data were not available for either the willow or poplar crops. In contrast, the annual yield data from the annual crops such as wheat and corn does capture year-to-year variation in weather patterns contributing to a stronger relationship in the PRISM-ELM model (Daly et al., 2018).

Previous assessments of environmental factors that contribute to yield in North America have generally identified climate as being a more important driver than soil. Fabio et al. (2017a) found that yield was positively correlated with longitude, growing degree days, and mean growing season precipitation, but not with the soil variables that were included. Liu (2013) found that about two-thirds of the variation in yield for a single willow cultivar across 18 sites could be explained by environmental variables and all of them were related to climate except elevation. None of the soil variables included in the model was significant.

The soils data used for the model was the best information available across the United States but was based on the classification of natural, unmanaged soils. These data do not reflect changes to soil conditions such as drainage, crop history or nutrient amendments prior to, or following the establishment of the poplar or willow plots, so not all soil management impacts are captured. Finally, the number of sites with woody crop yield trials was limited, especially in comparison with the expansive data set for annual wheat and corn crops, for which the relationship in the PRISM-ELM model was much stronger.

Despite the different approaches to modeling potential willow yield, the results from the PRISM-ELM and the BioCrop (Wang et al., 2015) models were fairly similar. The greatest yields were predicted for the Midwest region in both models. In general, the PRISM-ELM results had a smaller range where greater yields were projected. For example, yields from the PRISM-ELM model were predicted to be lower across the northern portions of the range (e.g., Wisconsin, Minnesota, Michigan, Maine) compared to the BioCrop model results. The same was true at the southern edge of the range, where the PRISM-ELM model yield projections were generally more conservative.

Conclusions

The PRISM-ELM model and the most extensive collection of shrub willow and hybrid poplar field trials available in the United States were used to develop potential national yield maps for these two woody energy crops. While the number of plots with measured or estimated yield was small compared to annual crops like wheat or corn where PRISM-ELM has been used, the relationships between predicted yield and measured yield were reasonably strong given the range of environments, ages, spacing, genotypes, and crop management. The results of these models provided an improved foundation for the development of biomass estimates from woody crops across the United States (U.S. Department of Energy, 2016) compared to approaches used previously (U.S. Department of Energy, 2011).

Over the past two decades, a number of willow trials have been established at multiple locations with different sets of genotypes produced through ongoing breeding. Fortunately, some of the key protocols for these trials have been consistent across many of the sites, which allowed data from a large number of these trials to be an input for these models. However, the range of environments where willow has been tested is limited, and there is a need to understand how the current suite...
of commercial cultivars perform on additional sites. It is particularly important to expand the range of soil and climate gradients where new willow cultivars are being tested in order to increase the level of confidence in willow yield predictions and to better understand G × E interactions.

Coppice-based biomass production systems using willow, and more recently poplar, are different than other dedicated energy crops because of their lifespan which includes multiple 2- to 4-year harvest cycles. At least seven cutting cycles are possible with willow, although the development of improved cultivars with higher yields may make it economically attractive to replace old cultivars with new ones before that point. Previous poplar trials have focused on longer rotations (5–13 year), but in recent years, there is a shift to studies on coppice systems. One of the unknowns with coppice systems is how yield changes over multiple cutting cycles that can cover a two- to three-decade life span for the crop. The limited data that are currently available for two rotations of coppice poplar and four rotations of willow suggest that there are changes in yield from the first to the second cutting cycle, but that changes in subsequent cutting cycles are more subject to weather conditions. There is a need to be able to monitor and measure changes in biomass of woody perennials crops through multiple cutting cycles, in order to gain a better understanding of yield responses and how to build these into yield, economic, and life cycle analysis models.

Willow biomass crops are just beginning to be deployed on a larger scale through planting subsidies provided by the US Department of Agriculture Biomass Crop Assistance Program in northern NY. Likewise, USDA NIFA has supported the establishment of large-scale hybrid poplar in the Pacific Northwest that have been managed through their first 3-year coppice cycles with yields measuring 18 Mg ha⁻¹ yr⁻¹ in Oregon’s Willamette Valley. While the information from the network of yield trials provides an essential foundation for predicting commercial yields, focused monitoring and measurements in these larger scale willow fields over the next few years will be important for making improvements to the system so it can be deployed more widely and profitably.

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