ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT PROGRAM

Identifying Suitable Areas for Woody Crop Production Systems in Wisconsin and Minnesota to Maximize Productivity, Increase Ecosystem Services and Meet Energy Feedstock Demands

Final Report
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Executive Summary

Short rotation woody crops (SRWC) such as *Populus* species and hybrids (hereafter referred to as poplars) are renewable energy feedstocks that can potentially be used to offset electricity generation and natural gas use in many temperature regions, such as Wisconsin and Minnesota, USA. Highly productive poplars grown primarily on marginal agricultural sites are an important component of our future Midwest energy strategy. Additionally, poplars can be strategically placed in the landscape to conserve soil and water, recycle nutrients, and sequester carbon. These purpose-grown trees are vital to reducing our dependence on non-renewable and foreign sources of energy used for heat and power. Establishing poplar genotypes that are adapted to local environmental conditions substantially increases establishment success and productivity. But, it is difficult to predict field trial success in landscapes where the crop has not been previously deployed.

To address this information shortfall, ***our overarching objective was to integrate large-scale biophysical spatial data and local-site information with 3-PG growth productivity modeling to assess where IMPPs can be established and grown with high expected returns and minimal impacts to the environment***.

We had five specific objectives:

1) Use available social (i.e., land ownership and cover) and biophysical (i.e., climate, soil characteristics) spatial data to map eligible lands suitable for establishing and growing poplar biomass and bioenergy crops across Minnesota and Wisconsin, USA.
2) Confirm the validity of this mapping technique by sampling and assessing biotic variables within eligible lands identified on the maps.
3) Parameterize, calibrate, and validate the 3-PG model for hybrid poplars in the region, and use the validated model to map potential biomass yields for Minnesota and Wisconsin.
4) Estimate potential poplar productivity within identified areas using 3-PG to determine spatial distribution of productive lands across the study area developed in 1).
5) Construct a comprehensive database of information pertaining to poplar growth and development to inform the mapping approach and poplar productivity modeling.

The database developed to inform much of the information in this study contains 862 unique citations that are cross-listed among up to three of thirteen topic areas, resulting in 1,398 total entries. Overall, eligible lands suitable for poplar production systems totaled 373,630 ha across both states; these lands represented 30.8% of the study area. Soil texture had the greatest influence on predicted biomass, which ranged from 9.5 ± 0.3 to 11.9 ± 0.2 Mg ha^{-1} yr^{-1} across both states, with an overall mean of 10.0 ± 0.1 Mg ha^{-1} yr^{-1}. Biomass predictions of specialist clones grown under optimal climate conditions (i.e., specialists) were 18% to 20% greater than their generalist counterparts, across both states. While this novel approach was validated for Minnesota and Wisconsin, our methodology was developed to be useful across a wide range of geographic conditions, irrespective of intra-regional variability in site and climate parameters. This is important because development and selection of appropriate energy crops lags behind anticipated need in most regions of the United States, especially the Midwest. Establishing poplar genotypes that are adapted to local environmental conditions substantially increases plantation success, subsequent productivity, and the ability of the trees to contribute to soil and water quality, nutrient recycling, and carbon sequestration. Failure to match proper genotypes with sites of deployment may curtail potential economic and environmental benefits associated with the dedicated poplar energy crops. Furthermore, success of these plantations and subsequent production of electricity and thermal energy using woody biomass can be used to offset electricity generation and natural gas use in Wisconsin, Minnesota, and other states.

Key Words

3-PG, biofuels, bioenergy, bioproducts, geographic information system (GIS), intensively-managed poplar plantations (IMPPs), *Populus*, productivity modeling, short rotation woody crops (SRWCs), site quality, yield

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List of Acronyms

CEC, cation exchange capacity

EC, electrical conductivity

ECEC, effective cation exchange capacity

FR, fertility rating

GDD, growing degree days

GIS, geographic information system

IMPP, intensively managed poplar plantation

NARR, National American Regional Reanalysis

NCEP, National Centers for Environmental Prediction

NLCD, National Land Cover Database

NOAA, National Oceanic and Atmospheric Administration

NOMADS, National Operational Model Archive and Distribution System

NRCS, Natural Resources Conservation Service

RMSE, root mean square error

SRWC, short rotation woody crops

SSURGO, Soil Survey Geographic Database

STATSGO, State Soil Geographic Database

UMGAP, Upper Midwest Gap Analysis

USGS, United States Geological Survey

Introduction

> **POPLARS EXHIBIT MANY ADVANTAGES RELATIVE TO OTHER ENERGY CROPS**
>
> *Examples include:*
>
> Energy per biomass unit of 16.5 to 17.2 MBtu per dry ton (swichgrass equals 13.0 to 15.5)
>
> Energy returned on energy invested of 13:1 (corn equals 1.3:1; switchgrass equals 5.5:1)
>
> Feedstock can be stored on the stump throughout the year until harvest
>
> Crop rotations can improve soil tilth
>
> Soil carbon storage rates increase throughout the rotation

The Energy Independence and Security Act (EISA) of 2007 contains provisions to increase the availability of renewable energy in the USA, and mandates the annual use of 36 billion gallons of renewable fuels by the year 2022 (EISA, 2007). Using baseline scenarios, Perlack et al. (2011) estimated that forestlands in the contiguous United States have the capability to produce 298 million dry Mg of biomass annually by the year 2030. Likewise, their baseline estimate for perennial crops (woody and herbaceous) on agricultural lands was 346 million dry Mg of biomass annually, with estimates for high-yield scenarios reaching 705 million dry Mg annually (Perlack et al., 2011). Production from both land cover types will be vital to meet the nation's demands for biofuels, bioenergy, and bioproducts.

Short rotation woody crops (SRWCs) are purpose-grown trees that are an integral component of this potential woody biomass supply. Following decades of tree improvement efforts (Stanton, 2009), fast-growing poplar genotypes have been identified, and these trees can be reproduced *en masse* using dormant vegetative cuttings. Poplars have many desirable qualities for use in biofuels, bioenergy, and bioproducts production, such as ease of propagation, well-known silviculture, and desirable wood and fiber quality, and they grow well in monocultural plantings, especially when given fertilization, weed control, and proper pest management (Stanturf et al., 2001; Coyle et al., 2005; Zalesny et al., 2011). Yields of intensively-managed poplar plantations (IMPPs) are commonly near 10 Mg ha^{-1} yr^{-1} (generalists), with values approaching 20 Mg ha^{-1} yr^{-1} for genotypes that are properly matched to site conditions (specialists) (Netzer et al., 2002; Goerndt and Mize, 2008; Zalesny et al., 2009; Pearson et al., 2010).

Production of renewable biomass at the level specified in EISA (2007) may result in large-scale land conversion (i.e., afforestation) across regions. This conversion leads to several questions regarding the economical, logistical, and ecological feasibility of increasing the amount of IMPPs in production in the USA, especially in areas where traditional agricultural crops are currently grown. Trees belonging to four genera comprise the majority of SRWCs grown in the USA: *Populus* (cottonwoods, poplars, aspens, and their hybrids), *Salix* (willows), *Pinus* (pines), and *Eucalyptus* (eucalypts) (Kline and Coleman, 2010; Zalesny et al., 2011). Among these options, intensively-grown poplars have gained substantial attention in the North Central region. Poplars are one of the most sustainable sources of biomass, and the tree improvement efforts described above have resulted in production management systems that support conservation of soil and water, recycling of soil nutrients, and preservation of genetic diversity (Hall, 2008). Despite these benefits, deployment of hybrid poplars has been hindered in part by our limited ability to predict the potential yields of sites not currently producing SRWCs.

Tree productivity is one of the most important factors in determining where new IMPPs are established. Lands with greater poplar productivity often result in higher cost efficiency, which helps mitigate economic and logistical concerns of landowners. By predicting IMPP growth and combining those data with biotic data, we can identify potential areas to establish IMPPs that have a high probability of success. Biomass yields are largely determined by (i) the combination of genetically-controlled, physiological processes which regulate tree growth, and (ii) the quality of the site, which is in turn influenced by climatological (e.g., precipitation, temperature, solar radiation) and soil factors (e.g., soil texture, soil water holding capacity, depth to water table). As such, a model that accounts for differences in these genotype- and location-specific characteristics is desirable. Physiological Processes Predicting Growth (3-PG) is a process-based model that uses species-specific physiological parameters, along with site-level climate and soil factors, to predict tree growth (Landsberg and Waring, 1997; Sands, 2004a; 2004b). While 3-PG has been used both to model growth and to estimate site productivity for eucalypt and pine species (Landsberg et al., 2003), and the model has been tested in Canada for hybrid poplar (Amichev et al., 2010) and willow (Amichev et al., 2011), similar reports for poplars in the U.S. are lacking.

Furthermore, while there is a substantial amount of land area that could be used for general bioenergy production (Cai et al., 2011), there are few data available to indicate the amount of land area available that could sustainably support commercial growth of poplars (Joss et al., 2008). Where data are available, they focus on cost effectiveness to the mill, and use coarse estimations for biomass growth potential (Husain et al., 1998). In addition, accurate maps depicting lands suitable for IMPP establishment and growth are lacking.

Objectives

To address the lack of information described above, ***our overarching objective was to integrate large-scale biophysical spatial data and local-site information with 3-PG growth productivity modeling to assess where IMPPs can be established and grown with high expected returns and minimal impacts to the environment***. The project builds on SRWCs research conducted at the Institute for Applied Ecosystem Studies in Rhinelander since 1968, as well as decades of poplar genetics research in Minnesota that has led to commercial poplar production on >10,000 ha in the state.

More specifically, we had five objectives:

1) Use available social (i.e., land ownership and cover) and biophysical (i.e., climate, soil characteristics) spatial data to map eligible lands suitable for establishing and growing poplar biomass and bioenergy crops across Minnesota and Wisconsin, USA.

2) Confirm the validity of this mapping technique by sampling and assessing biotic variables within eligible lands identified on the maps.

3) Parameterize, calibrate, and validate the 3-PG model for hybrid poplars in the region, and use the validated model to map potential biomass yields for Minnesota and Wisconsin.

4) Estimate potential poplar productivity within identified areas using 3-PG to determine spatial distribution of productive lands across the study area developed in 1).

5) Construct a comprehensive database of information pertaining to poplar growth and development to inform the mapping approach and poplar productivity modeling.

This protocol was developed to be useful across a wide range of geographic conditions, irrespective of intra-regional variability in site and climate parameters. Thus, this information is vital for siting poplar energy production systems to increase productivity and associated ecosystem services, and is widely applicable to woody biomass production systems worldwide. This information is important for industry leaders, policymakers, and resource managers when making decisions whether to site bioenergy facilities in areas where limited yield data are available and when limited information is known about the potential impacts of growing IMPPs on local and regional ecosystem services.

Objective 1: Mapping Eligible Lands

Methods

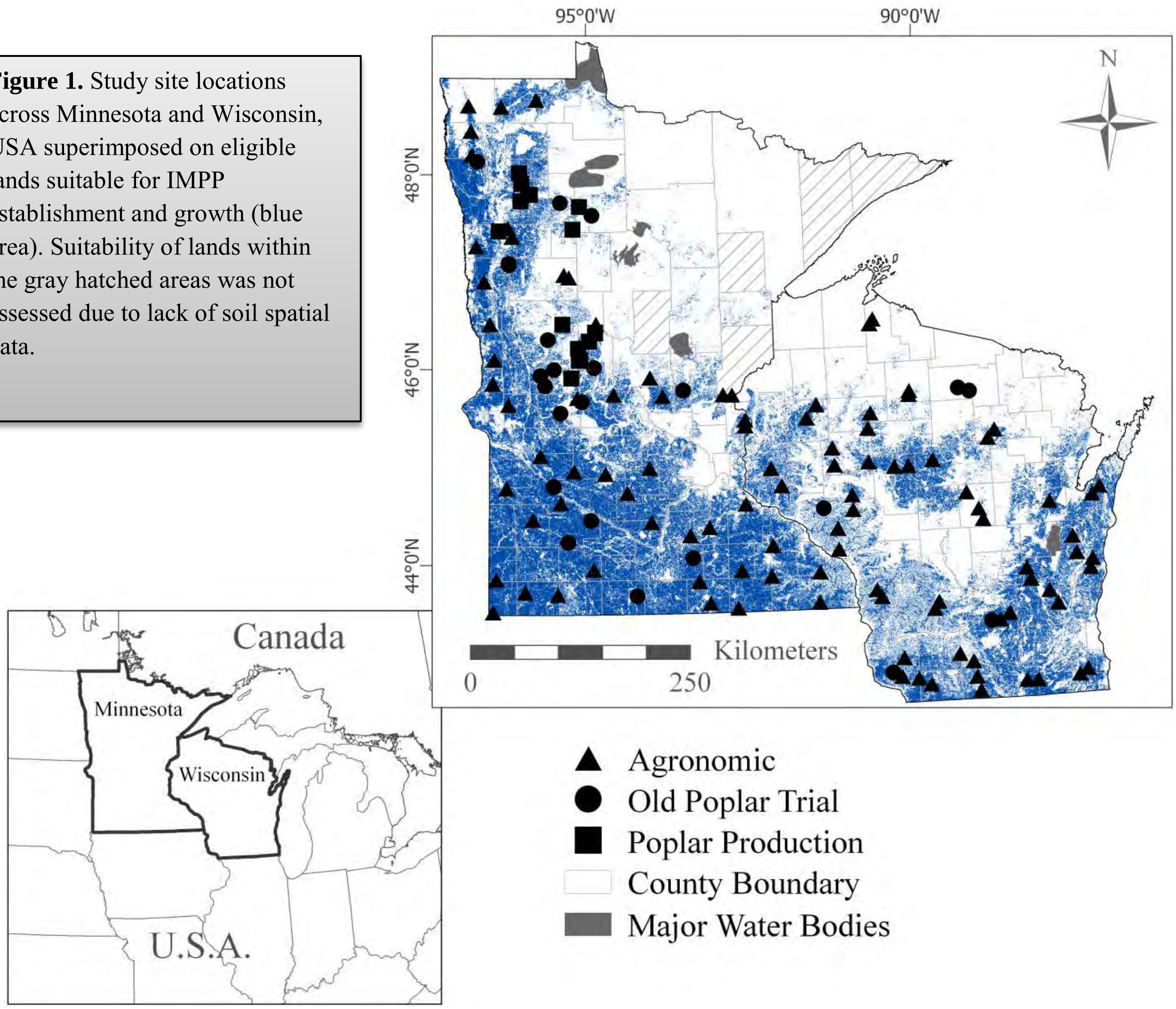
Identifying Suitable Lands

Our approach to identifying lands suitable for poplar production systems consisted of determining lands eligible for IMPPs based on land use/land cover and ownership, and then further refining those lands based on local-scale soil characteristics known to be important for the establishment and growth of available genotypes of these IMPPs. We defined lands eligible for conversion to poplars as those having mesic soils with adequate water availability, on private lands with open, herbaceous land cover types (based on the assumption that the establishment of IMPPs in the near future will not involve converting forests or shrublands, nor occur on public forests). Because local-scale soil factors influence tree growth and productivity (Powers et al., 2005; Pinno et al., 2010), we incorporated local-scale soil characteristics that influence soil water and nutrient availability; specifically, available water storage and soil texture. We overlaid this base map showing potential lands for afforestation with temperature-precipitation gradients to identify sites across a wide range of environmental conditions for field reconnaissance. Figure 1 illustrates the map of eligible lands, along with field sites used for field reconnaissance in Objective 2.

Land cover data were obtained from the 2006 National Land Cover Database (NLCD) classification scheme of the U.S. Geological Survey (USGS), which represents classified 30-m resolution Landsat Thematic Mapper satellite data (Fry et al., 2011). We selected grassland/herbaceous, pasture/hay, and cultivated crop vegetation classifications to represent land covers most likely to be converted into poplars. Based on NLCD definitions, grassland areas are dominated (>80% of total vegetation) by grammanoid or herbaceous vegetation, and are not subject to intensive management such as tilling, but can be grazed. Pasture/hay areas are dominated by grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation. Cultivated crops are areas used for the production of annual crops, such as corn, soybeans, vegetables, and perennial woody crops such as fruit orchards. Crop vegetation accounts for greater than 20% of total vegetation, and includes all land being actively tilled.

Land ownership data were obtained from the USGS Upper Midwest Gap Analysis Program (UMGAP), Minnesota and Wisconsin stewardship programs (USGS, 2005). All lands classified as federal, state, county, and tribal were considered public lands, and were excluded from the base layer.

Figure 1. Study site locations across Minnesota and Wisconsin, USA superimposed on eligible lands suitable for IMPP establishment and growth (blue area). Suitability of lands within the gray hatched areas was not assessed due to lack of soil spatial data.



We obtained soil property variables from the Soil Survey Geographic (SSURGO) database. We retrieved available water storage (aws0100wta) and soil texture (texdesc) data associated with each soil map unit within our defined base layer from the SSURGO data tables of muaggatt and chtexturegrp. Given the importance of soil texture on poplar establishment and growth, along with the positive relationship between soil texture and soil water availability, we included 26 textures in the base map according to suitability ratings of Schroeder et al. (2003) (Table 1). In addition, we used available water storage capacity of ≥14 cm in the top 100 cm. Available water capacity is the volume of water the soil can store that is available to plants (NRCS 1998). Spatial datasets were assembled and queried using Spatial Analyst within ArcGIS software (ESRI, Inc., Redlands, CA, USA).

Table 1. Classification scheme for assigning soils to default 3-PG soil classes. The SSURGO soil textures were used for base map development, while the site textures were those sampled from the 143 field plots and used for QA/QC analyses.

3-PG Soil Class	SSURGO Texture	Site Texture	Approximate Composition
Clay[a] (C)	None	Silty clay	>40% clay
Clay Loam (CL)	Clay loam, fine loam, sandy clay loam, silty clay loam	Clay loam, sandy clay loam, silty clay loam	20-40% clay
Sandy Loam (SL)	Coarse loam, coarse sandy loam, coarse silt, fine sandy loam, fine silt, gravelly loam, gravelly sandy loam, gravelly coarse sandy loam, gravelly fine sandy loam, gravelly silt loam, loam, sandy loam, sandy over loam, silt loam, silt, very fine sandy loam, very gravelly loam, very gravelly sandy loam	Loam, sandy loam, silt, silt loam	<20% clay, <80% sand
Sand (S)	Loamy coarse sand, loamy fine sand, loamy very fine sand, loamy sand	Loamy sand, sand	<20% clay, >80% sand

[a]Suitable soil textures for base map development were based on those deemed highly suitable and suitable by Schroeder et al. (2003); those classified as marginally suitable (e.g., with >40% clay content) were not considered in the current study.

Climatic Variables

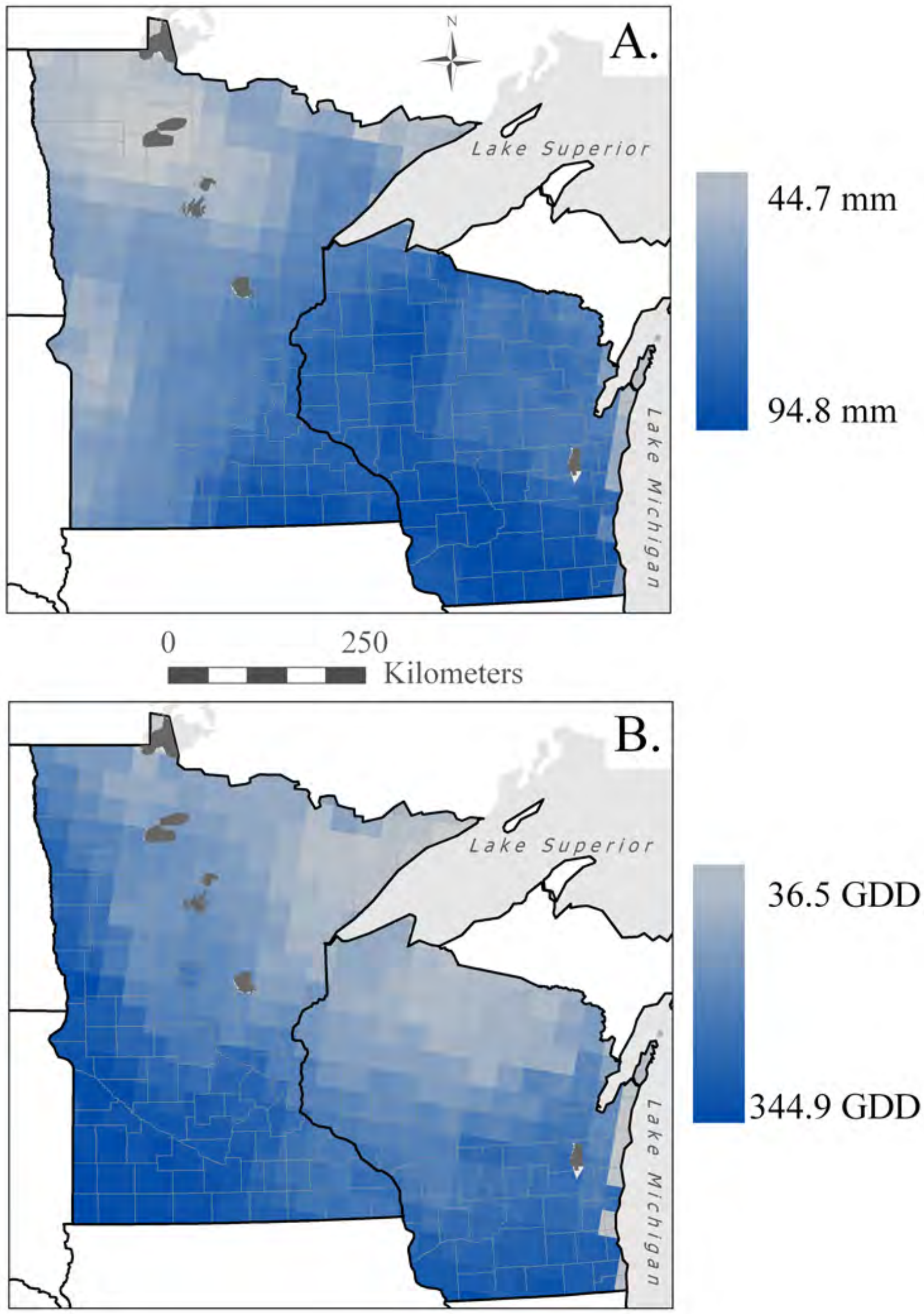
Regional and landscape-scale climate conditions greatly influence the establishment and growth of poplars (Hogg et al., 2005; Welham et al., 2007; Joss et al., 2008). Because our study area crossed over several climatic regimes with variable temperature-moisture gradients, climate will impact the productivity of poplars at local scales such that specific genotypes will need to be deployed across particular geographic locations to maximize productivity. Specifically, our study area crossed three ecoregional provinces as defined by the National Hierarchical Framework of Terrestrial Ecological Units (Cleland et al., 2007). Ecoregional provinces represent climatic gradients where the boundaries are zones of transition reflecting subtle continuous changes in macroclimate rather than abrupt, discrete changes. The Laurentian Mixed Forest Province covers northeastern Minnesota and the northern third of Wisconsin where the climate is influenced by the Great Lakes, and most precipitation occurs during the warm summers. Winters are moderately long with continual ground snow cover. The western edge and southwest corner of Minnesota are covered by the Prairie Parkland (Temperate) Province that is characterized by cold winters and warm summers, and receives moderate precipitation mainly during the growing season. Between these provinces is the Midwest Broadleaf Forest Province that runs from the northwest corner of Minnesota to southeastern Minnesota and covers the southern half of Wisconsin. This region is characterized by warm to hot summers, and frequent growing season water deficits causing mild, brief droughts.

We used the North American Regional Reanalysis (NARR) dataset (http://wwwt.emc.ncep.noaa.gov/mmb/rreanl; Mesinger et al., 2006) to obtain climate variables across our study area. The NARR Project is a reanalysis of historic meteorological observations using a 32-km version of the National Centers for Environmental Prediction (NCEP) 1993 operational Eta model and Eta data assimilation system (EDAS). By assimilating precipitation and radiances, and using a more comprehensive land-surface model (Ek et al., 2003), the NARR allows the land-surface model to interact with realistic precipitation creating a high-resolution, atmospheric and land surface hydrology dataset for the North American domain. The NARR gets improved estimates of surface hydrologic and near-surface meteorological fields. Data consist of 3-hour output observations across the North American domain at a 32-km grid resolution.

From the National Oceanic and Atmospheric Administration (NOAA) National Operational Model Archive and Distribution System (NOMADS) website, we obtained historic 3-hour monthly means for surface total precipitation (APCPNsfc), air temperature at 2 m above ground level (TMP2m), and daily surface downward shortwave radiation flux (DSWRFsfc) from 1999 to 2008. Data consisted of eight 3-hr observations per month across the 10 years for a total of 960 observations per climate variable. Each observation represents the average daily value during that month for each 3-hr increment. To calculate the 10-year average accumulated precipitation for all months individually, we summed the 3-hr monthly means, multiplied the summed value by the number of days in each month, and then averaged across the 10 years. For temperature, we selected the minimum and maximum 3-hr monthly mean air temperature recorded for each month, and averaged these values across the 10 years to obtain the 10-year monthly average minimum and maximum air temperature. The 10-yr average downward shortwave radiation flux for each month was calculated by averaging the eight 3-hr values by month, and averaging these values across the 10 years.

The NARR climate data were geo-referenced with latitude and longitude coordinates that were used to attribute a 32-km base grid generated to correspond to the Lambert conformal (AWIPS) grid (Mesinger, 2006). These attributed grids demonstrate the gradients in temperature and precipitation across the land base (Figure 2). Growing degree days (GDD) are illustrated as a surrogate for temperature to reflect annual accumulated heat sums, which are vital for growth and development of the trees, as well as a potentially useful parameter for determining planting dates for the productivity modeling described below. To calculate the 10-year average annual GDD, we summed the 3-hr average daily value air temperature observations that were above 14 °C (Zalesny et al., 2005) and divided by 8, which was then multiplied by the number of days in the month to get a monthly heat-sum [GDD]. Each consecutive monthly value was summed to the previous month to calculate the accumulating heat-sum. The final month, December, is the GDD for each year. Finally, the annual GDD values were averaged across the 10 years.

Figure 2. Average total annual precipitation (A.) and average total annual growing degree days (B.) for Minnesota and Wisconsin, USA (1999 to 2008). See Methods for a description of how growing degrees days were calculated.



Results

Potential Land Base Suitable for IMPPs

Eligible lands suitable for IMPPs were identified throughout Minnesota (249,990 ha) and Wisconsin (123,641 ha) totaling 373,630 ha (Figure 1); these lands represented 30.8% of the two-state area. The majority of the suitable lands are currently cultivated crops (79.1%) followed by pasture/hay and grassland (17.8% and 3.1%, respectively). The highest densities of suitable lands were identified in the south and west regions of Minnesota, and the southeast and central regions of Wisconsin. These regions represent areas that are currently used for agriculture, or have open grasslands/pastures such as in the center portion of Wisconsin. The absence of eligible lands in the northern portion of Wisconsin is attributed to the large amount of public lands (e.g., national, state and county forests, and Native American Reservations), which by definition were excluded, and due to areas dominated by sandy soils with low water storage capacity such as the Central Sands area in the center of Wisconsin and the northwestern counties making these areas unsuitable for IMPPs. There were also several areas in northern Minnesota where suitability could not be assessed due to the absence of SSURGO data (Figure 1), but the predominance of public lands in much of these areas excluded the lands from being eligible for establishing IMPPs.

Objective 2: Field Reconnaissance

Methods

Data Collection

During 2009 and 2010, we conducted field reconnaissance to assess the validity of the spatial modeling and assess the potential opportunities for maintaining soil health, water quality, and other ecosystem services, assuming poplars are tested and/or deployed within eligible lands defined above. We identified large, contiguous areas on the base map that were deemed suitable for poplar production and were well-distributed spatially to represent a full spectrum of climate conditions found across Minnesota and Wisconsin. We then traveled to these areas, and identified specific sites in the field that were within suitable areas on our base map. We excluded sites in developed areas that included houses, lawns, or were obviously landscaped. We chose areas in fields, woodlands, pastures, and the sides of waterways, but avoided areas that appeared to have been overly compacted or under running water (e.g., field driveways and waterways). In addition, we traveled to and included two site types currently producing poplars: 1) historical poplar plantations belonging to a regional U.S. Department of Energy testing network established in 1988 to 1991, and 2) current poplar production plantings.

We recorded landscape variables including site cover type (agronomic, old poplar field trial, current poplar production), current vegetation, slope class, surface stoniness, soil drainage and erosion risk classes (Table 2), water drainage, and latitude and longitude. Overall characterization of site suitability for trees was also determined.

Table 2. **Descriptions of soil drainage and erosion risk classes (from Schroeder et al., 2003).**

Drainage Class	**Description**
Rapidly drained	The soil moisture content seldom exceeds field capacity in any horizon except immediately after water additions (soils are free from gleying throughout the profile)
Well drained	The soil moisture content does not normally exceed field capacity in any horizon (except possibly the C) for a significant part of the year (soils are free from mottling in the upper 1 m)
Moderately well drained	The soil moisture in excess of field capacity remains for a small but significant period of the year (soils are mottled in the bottom of the B and C horizons)
Imperfectly drained	The soil moisture in excess of field capacity remains in subsurface layers for moderately long periods of the year (soils are mottled in the B and C horizons)
Poorly drained	The soil moisture in excess of field capacity remains in all horizons for a large part of the year (soils are usually very strongly gleyed)
Erosion Class	**Description**
Very low	Good soil management and average growing conditions will produce a crop with sufficient residue to protect these soils from erosion
Low	Good soil management and average growing conditions may produce a crop with sufficient residue to protect these soils against erosion
Medium	Average growing conditions may not supply adequate residue to protect these soils against wind erosion, and enhanced soil management practices are necessary to control erosion
High	Average growing conditions will not provide sufficient residue to protect these soils against erosion
Very high	These soils should not be used for annual cropping, but rather for pasture and forage crops which will protect the surface from severe degradation

Soil samples were collected at three locations separated by at least 10 m at each site. One soil sample (3.8 cm dia.) to a 30 cm depth was collected from each sample point using a stainless steel soil core sampler with a plastic liner (AMS Inc., American Falls, ID, USA). In the field, qualitative assessments were performed for soil structure and presence of horizons and/or gleying at the bottom of the cores. After collection, each sample was held at ambient temperature and returned to the U.S. Forest Service, Institute for Applied Ecosystem Studies in Rhinelander, WI, USA. Soils were stored at 5 °C until being carefully removed from the plastic liners. One half of the sample (from ground level to 30 cm depth) was archived and held at the Rhinelander Laboratory, while the other half was composited to produce one sample per study site (i.e., half of the soil from each of the three samples per site was bulked). These composited soil samples were air dried and hand-crushed to pass through a 2 mm mesh screen and sent to the University of Wisconsin Soil Testing Laboratory in Verona, WI, USA for soil texture determination. The archived samples were similarly sieved, ground through a 0.5 mm screen using a Cyclotec 1093 grinder (FOSS Analytical A/S, Eden Prairie, MN, USA), and analyzed for the following parameters: *pH* using a Fisher Scientific Accumet Model No. XL50 pH meter with a combination reference-glass electrode (Fisher AccuCap combination pH electrode; Fisher Scientific, Waltham, MA, USA); *electrical conductivity* (EC) using the same meter with a Fisher Accumet temperature-compensated two-cell conductivity probe; *nitrogen* and *carbon* content using a Flash EA1112 N-C analyzer with a model MAS 200 autosampler (Thermo Electron, via CE Elantech, Inc., Lakewood, NJ, USA); and concentrations of base cations (*Ca, Mg, K, Na*) and cobalt (*Co*) via atomic emission (AE) spectroscopy using a Varian Agilent model 240 FS AA unit (Agilent Technologies, Englewood, CO, USA). *Cation exchange capacity* (CEC) was calculated

by summing the base cations, and *effective cation exchange capacity* (ECEC) was determined by the cobalt hexamine trichloride method described by Ciesielski and Sterckeman (1997), whereby the difference of the Co level measured compared to the initial Co level in the blank extraction solution reflects the ECEC.

Validation of Soils Information

We evaluated the accuracy of soils data from the SSURGO database relative to field soils data to assess the reliability of the spatial analysis protocol for describing the sites that have the potential to be used for poplar production (i.e., QA/QC). Specifically, we grouped both SSURGO and field textures into the four 3-PG soil classes listed in Table 1 and recorded success when both sources belonged to the same 3-PG group. Similarly, for pH and CEC, we used two methods to assess whether SSURGO and field data were comparable. For method 1 (hereafter referred to as the "strict sense" method), successful matches occurred when the range of field pH/CEC fell completely within that of the range reported in the SSURGO data; for method 2 (hereafter referred to as the "loose sense" method), successful matches occurred when the range of field pH/CEC overlapped either or both ends of the SSURGO data range. In addition, success rates were evaluated non-parametrically using a Chi-square ($\chi2$) test from frequency counts to analyze differences among the site cover types defined above to assess whether certain land uses affected soil properties to the point that the soil surveys were less accurate. For these analyses, agronomic sites were split into annual and perennial groups, and the two poplar cover types were combined. Thus, we tested for differences among annual, perennial, and poplar land cover. Furthermore, empirical data from prior regional field testing networks were combined with the process-based productivity modeling described below to predict establishment and long-term yield of favorable genotypes throughout the eligible lands.

Results

Field Site Information

A total of 143 sites were sampled: 84 in Minnesota and 59 in Wisconsin (Figure 1; Appendix A). Agronomic land cover type dominated both states, but the current vegetation was much more diverse in Minnesota (Appendix A). Minnesota also had a lower percentage of sites with corn (MN = 19%, WI = 49%), alfalfa (MN = 8%, WI = 17%), and soybeans (MN = 13%, WI = 19%), but had a greater number of poplar sites (40%) compared with Wisconsin (8%).

Soil texture and chemistry were highly variable across our sampling area (Appendix B). Sandy loam and loam were the most common soil types in Minnesota, while silt loam was the dominant soil texture encountered in Wisconsin (Figure 3). Pooled data indicated that silt loam and sandy loam were the most common soil types in our study areas (Figure 3). Study sites in Minnesota were less sloped than Wisconsin, but overall most slopes were 5% or less (Figure 3). Very few sites had slopes >15%. Over 70% and 98% of the sites in Minnesota and Wisconsin, respectively, had acceptable drainage risk classes for IMPPs (Table 3). Erosion risk class ratings were very similar to drainage risk class ratings, and when data were pooled over 81% and 85% of sampled sites had acceptable drainage and erosion risk class ratings, respectively (Table 3). Surface stoniness was negligible, with <1% of sites being classified as having stones that seldom hinder cultivation; those data are not presented.

Figure 3. Soil texture and slope class across study sites in Minnesota and Wisconsin, USA.

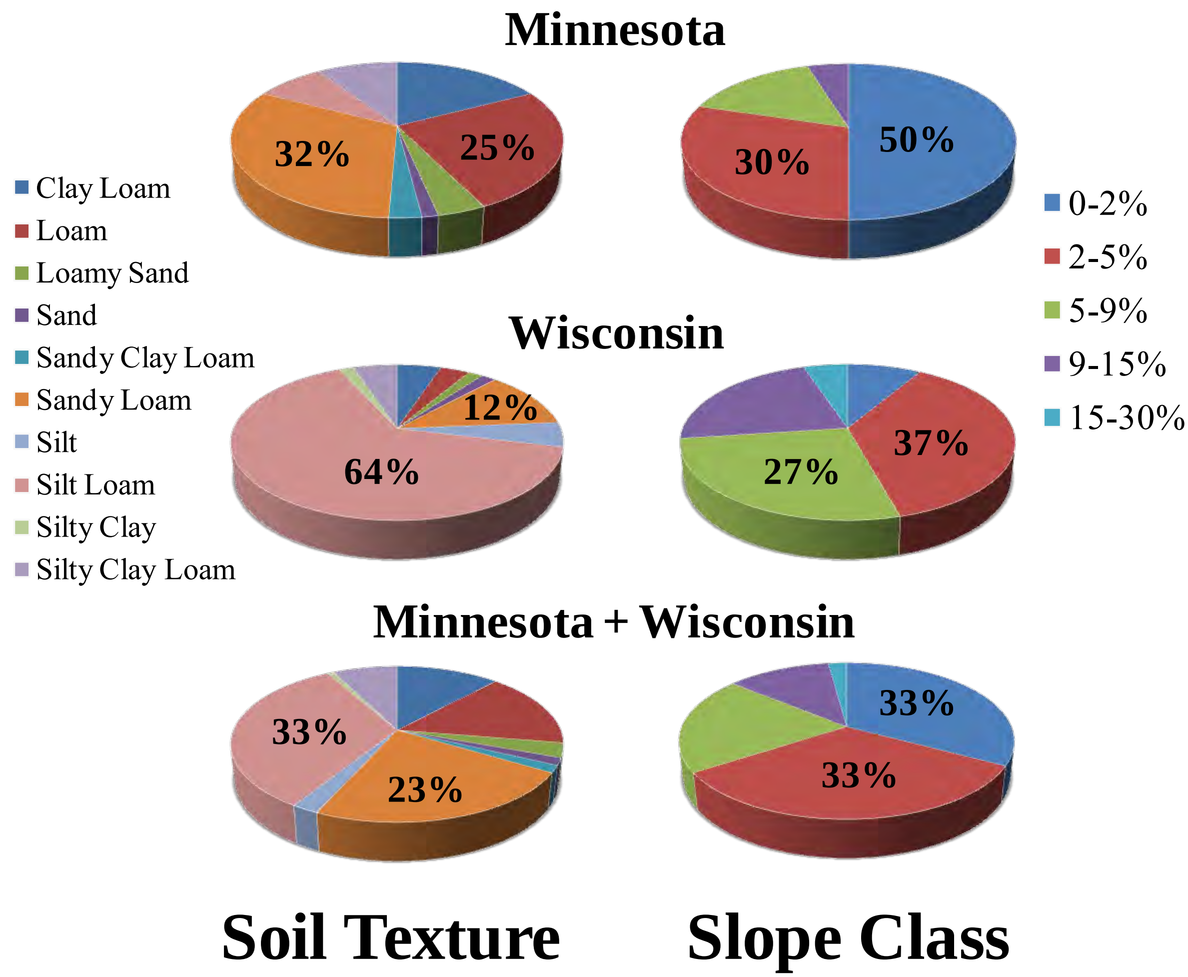


Table 3. **Percentage of sites deemed acceptable and unacceptable based on soil drainage and erosion risk classes defined in Schroeder et al. (2003). Poorly and imperfectly drained soils were classified as unacceptable, as were sites with high and very high erosion potential.**

	Drainage		**Erosion**	
State(s)	**Acceptable**	**Unacceptable**	**Acceptable**	**Unacceptable**
Minnesota	70.2	29.8	76.2	23.8
Wisconsin	98.3	1.7	98.3	1.7
Minnesota + Wisconsin	81.8	18.2	85.3	14.7

Comparison of SSURGO Soils Data with Field Data

The percent accuracy of SSURGO soils data relative to field data for texture, pH, and CEC ranged from 48% to 85%, with the lowest rate of successful matches being for CEC when using the strict sense method (Table 4). The rigid criteria of the strict sense method translated to reductions in accuracy of 25% for CEC and 18% for pH across all sites, relative to the broader constraints of the loose sense method. In contrast, methodological differences were negligible for both pH and CEC when comparing the reliability of SSURGO data among land cover types (annual, perennial, and poplar). The range in percent success between the methods differed by 6% for pH and 2% for CEC. In general, the SSURGO data were most accurate for perennial land cover. However, the differences in accuracy among land cover types were not significant for texture (P = 0.7636), pH (P_{strict} = 0.3075; P_{loose} = 0.6643), or CEC (P_{strict} = 0.2060; P_{loose} = 0.3044).

Table 4. **Percent accuracy of SSURGO soils data relative to field data at sites with annual, perennial, or poplar land cover for texture, pH, and cation exchange capacity (CEC). The number of successful matches out of the number of possible sites is listed in parentheses.**

		pH		CEC	
Cover	**Texture[a]**	**Method[b] 1**	**Method 2**	**Method 1**	**Method 2**
Annual	78	71	84	45	74
	(62/80)	(57/80)	(67/80)	(36/80)	(59/80)
Perennial	83	70	91	65	83
	(19/23)	(16/23)	(21/23)	(15/23)	(19/23)
Poplar	74	58	85	45	65
	(23/31)	(23/40)	(34/40)	(18/40)	(26/40)
Total	78	67	85	48	73
	(104/134)	(96/143)	(122/143)	(69/143)	(104/143)

[a]Field soil texture data were not available for nine Minnesota poplar sites.
[b]For Method 1, successful matches occurred when the range of field pH/CEC fell completely within that of the SSURGO data; for Method 2, successful matches occurred when the range of field pH/CEC overlapped either or both ends of the SSURGO data range.

Objective 3: Parameterization, Calibration, and Validation of 3-PG

Methods and Results (combined given step-wise nature of the modeling)

General Information

The Physiological Processes Predicting Growth (3-PG) model was (i) parameterized for poplars using species-specific physiological data and allometric relationships from previously-published studies, (ii) calibrated for the North Central region using previously-published biomass data from eight plantations along with site-specific climate and soils data, (iii) validated against previously-published biomass data from four other plantations using linear regression of actual versus predicted biomass (R^2 = 0.89, RMSE = 8.1 Mg ha^{-1}), (iv) evaluated for sensitivity of the model to manipulation of the parameter for age at full canopy cover (fullCanAge), and (v) combined with soil and climate data layers to produce a map of predicted biomass for the states of Minnesota and Wisconsin.

Model Parameterization

Literature-Derived Parameters

The spreadsheet-based version of 3-PG (known as 3-PGpjs) was obtained from the Commonwealth Scientific and Industrial Research Organization (CSIRO) headquartered in Canberra, Australia. Users can enter species-specific values for up to 60 parameters that describe tree physiology and allometric growth relationships. Each can be classified in terms of how sensitive the model is to manipulation of the parameter (Sands, 2004b). A review of previously published poplar research was conducted to determine values for these parameters, with a particular focus on those in the high-sensitivity class. When available in the literature, parameter values for the specific clones modeled in the calibration and validation phases were used; otherwise, parameter values derived from the parent species (pure or crossed with other species) were used. For some of the values reported in the literature, conversions were necessary to match the input units of the model. For others (particularly several allometric relationships), the parameters were estimated (algebraically, graphically, or via linear regression) based on values and/or equations reported in the literature. Table 1 of Appendix C lists the parameters derived from the literature review, their sensitivity class, and the values assigned to poplars for this study; Appendix C also describes the procedures used when parameters were estimated from values and/or equations reported in the literature.

Intuitively-Assigned Parameters

For several parameters, intuitive values based on the knowledge and experience of the authors and their collaborators were used (Table 2 of Appendix C). Age at median litterfall rate (t_{gammaF}) was set at 18 months so that the plateau for mature litterfall rate would be reached at approximately the time of canopy closure. Seedling mortality rate ($gammaN_0$), large tree mortality rate ($gammaN_X$), age at median mortality rate (t_{gammaN}), and shape of the mortality curve (n_{gammaN}) were assigned values which simulate a 5 percent mortality rate concentrated early in the rotation; this is considered typical for poplar plantations in the region (Dan Langseth, Verso Paper Corp., personal communication). Age at average specific leaf area (t_{SLA}) was assigned based on the relationship between specific leaf area (SLA) and height reported by Smith et al. (2011), in which they showed the average SLA for *P. tremuloides* occurred at heights of approximately 7.5 to 10 meters; similar heights are frequently achieved around age 5 for the poplars considered in this study. One parameter (age at full canopy cover; fullCanAge) was assigned its value using an iterative approach for maximizing model fit; this is described further in the calibration section.

Default Parameters

For the remaining parameters, default values were used (Table 3 of Appendix C). Several are conversion factors, and all are identified by Sands (2004b) as parameters which may be assigned generic values.

Model Calibration

Regional calibration of 3-PG requires (at minimum) growth data from multiple sites, and climate and soil data for each of the sites. Calibration also typically involves manipulation of unknown parameters as well as growth modifiers to optimize the fit of the model to the dataset (Sands, 2004b). The following sections describe the biomass, climate, and soils data used in this study, as well as the procedures used for manipulating our unknown parameter (fullCanAge) and the fertility rating (FR) growth modifier.

Biomass Productivity Data

Netzer et al. (2002) reported poplar biomass for a number of sites planted at former agricultural fields in the North Central region in 1987 and 1988. In that study biomass yields (averaged across 25-tree blocks of each of the *Populus deltoides* × *P. nigra* hybrids DN17, DN34, and DN182) were reported for 12 plantations in Wisconsin, Minnesota, and the eastern Dakotas planted at 2.4 × 2.4-meter spacing and measured at various ages (ranging from 3 to 11 years). This dataset (81 total datapoints) was used for model calibration (56 datapoints from 8 plantations) and validation (25 datapoints from 4 plantations; see Table 5). Clone-specific data were also reported for ages 8 to 11 for the same sites; however, analysis of variance showed no significant difference in biomass across sites for the three clones ($P = 0.37$). As a result, the data averaged across clones was used in this study, based on the wider range of ages for which the data were available.

Table 5. Plantations from Netzer et al. [30] used for calibration and validation of 3-PG for hybrid poplars.

Dataset	Site	Location	Year Planted	# Years of Data	Latitude (ºN)
Calibration	ASH87	Ashland, WI	1987	6	46.63
	ASH88	Ashland, WI	1988	5	46.63
	FRM88	Fairmont, MN	1988	6	43.68
	GRF87	Granite Falls, MN	1987	7	44.80
	GRF88	Granite Falls, MN	1988	6	44.80
	MIL87	Milaca, MN	1987	9	45.77
	MON8	Mondovi, WI	1987	9	44.87
	MON8	Mondovi, WI	1988	8	44.87
Validation	CLO88	Cloquet, MN	1988	7	46.83
	FAR87	Fargo, ND	1987	6	46.90
	SXF87	Sioux Falls, SD	1987	6	43.57
	SXF88	Sioux Falls, SD	1988	6	43.57

Climate and Soils Data

Monthly climate data (total precipitation, mean daily maximum temperature, mean daily minimum temperature, and mean daily solar radiation) were determined from the weather stations nearest each site for the specific years that the plantations were grown; these data are summarized in Table 4 of Appendix C. In addition, relevant soils data (texture, maximum available soil water, and depth to water table) were determined for each site (Table 5 of Appendix C) based on published soil surveys.

Because available water in the top meter of soil is typically considered accessible to plants (USDA, 1998), maximum available soil water (ASW_{max}) was set equal to that reported in the soil survey for the top 100 cm. Minimum available soil water (ASW_{min}) was set as a proportion of ASW_{max} based on minimum annual depth to water table (D_w) as follows:

$$ASW_{min} = ASW_{max}\left(1 - \frac{D_w}{100}\right) \quad (1)$$

where any D_w greater than 100 cm is assigned a value of 100.

Other cutoffs for water table depth (50, 150, and 200 cm) were also evaluated; however, their use did not improve the fit of the model relative to using a depth of 100 cm (results not shown). Because the plantations were established during what Netzer et al. (2002) described as a "historic (100 year) drought", the initial value of ASW for each site was set equal to ASW_{min}. The soil texture for each site was matched to the most appropriate of the default categories found in 3-PG (C = clay, CL = clay loam, SL = sandy loam, S = sand) based on approximate clay and sand content (Table 1).

Optimizing Model Fit

For fitting the model to the calibration sites, the fertility rating (FR) growth modifier and full canopy age (fullCanAge) parameter were systematically manipulated to determine the best-fit values for the overall model; essentially, these best-fit values represent the average values of FR and fullCanAge across all sites. The FR growth modifier has a value between 0 and 1 and acts as a multiplier to adjust potential growth based on relative nutrient availability; the fullCanAge parameter represents the year at which canopy closure occurs. The potential values of FR and fullCanAge were evaluated under the assumptions that (i) it is possible all the sites have FR ≈ 1, based on potentially high levels of residual nutrients associated with the agricultural history of all the sites, and (ii) if the first assumption is not true then, given the number of sites, the range of potential values for FR in the region should be reasonably represented and therefore at least one site should have FR ≈ 1.

Decreasing values of FR result in lower estimates of biomass, whereas decreasing values of fullCanAge result in higher estimates of biomass; thus, for a given level of productivity, a decrease in fullCanAge must be met with a decrease in FR. Based on these assumptions, it is possible to (i) establish the upper limit for fullCanAge by assuming FR = 1 and reduce fullCanAge in 1-year increments from its highest possible value (11 years) until the best-fit value is found, (ii) establish the lower limit for fullCanAge by further reducing the parameter in 1-year increments (with FR = 1) until the best-fit value is found for the last (most under-predicted) of the individual sites, (iii) determine the best-fit value of FR for each value of fullCanAge within these upper and lower limits, by iteratively reducing FR from its highest possible value (1, unitless) in increments of 0.05, and (iv) compare the fit statistics (R^2 and root mean square error, RMSE) for each resulting combination of FR and fullCanAge, to determine the best-fit average values of FR and fullCanAge for the sites.

Using this approach, the upper limit for average fullCanAge was estimated to be 5 years, and the lower limit was estimated to be 3 years. For each value of fullCanAge within these limits, FR was reduced until the best-fit model was achieved (with the requirement that systemic bias [universal over-prediction or under-prediction] be avoided). The resulting combinations of fullCanAge and FR, along with fit statistics, are shown in Table 6 of Appendix C. Because the combination of FR = 1 and fullCanAge = 5 produced the best fit (R^2 = 0.88, RMSE = 8.8 Mg ha^{-1}), these values were used for the remainder of the study; however, it should be noted that the fit statistics for the other combinations were relatively similar, and therefore if used are likely to give similar results.

Model Validation

The calibrated model was used to predict biomass productivity of the four plantations assigned to the validation dataset (described in the preceding section) across the range of ages for which biomass data were available from Netzer et al. (2002). Soil and climate data were obtained for the validation sites in the same manner as described for the calibration sites. All other model settings (tree spacing, initial ASW, FR, fullCanAge) were the same as for calibration. The fit of the model to the validation dataset, as determined by linear regression of actual biomass on predicted biomass, is shown in Figure 4 ($R^2 = 0.89$, RMSE = 8.1 Mg ha^{-1}).

In addition to the fit of the model overall, model fit for the individual sites was also evaluated. Linear regression was conducted using PROC GLM in SAS (SAS Institute Inc., Cary, NC) to determine the slope and intercept for the correlation between actual and predicted biomass for each site (Figure 1 of Appendix C). The values ranged from 0.70 to 1.18 for the slopes, and -13.2 to 17.6 for the intercepts. To examine the relationship of individual sites relative to the overall model, we tested the hypotheses of equal slopes and intercepts. A surrogate site (MON87) was selected to represent the overall model, based on similarity of slope and intercept. Statistical contrasts were then conducted in SAS to compare the slope and intercept of the surrogate site to those of the remaining sites. The results show evidence of a difference in slope for FRM88 (P = 0.0055), and differences in intercepts for FAR87 (P = 0.0158), GRF87 (P = 0.0205), MON88 (P = 0.0056).

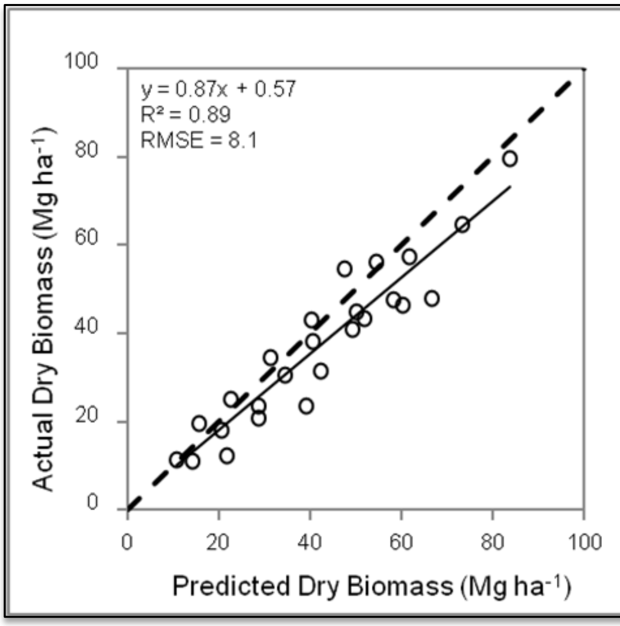


Figure 4. Fit of the calibrated model to the data used for validation.The dashed line represents 1:1 ratio of actual versus predicted dry biomass.

Finally, the ability of the model to effectively identify high versus low productivity sites is of interest for siting bioenergy facilities and the poplar plantations which would supply them. Actual and predicted biomass growth over time is shown for plantations established in 1987 (Figure 5) and 1988 (Figure 6).

Sensitivity Analysis

The sensitivity of the model, as calibrated for poplars in the region, was evaluated by manipulating fullCanAge. This parameter was selected due to the uncertainty of its true value(s); the parameter was estimated via model optimization during the calibration phase of the study. Fertility rating (FR) was also estimated during the calibration phase, but was not evaluated in the sensitivity analysis, because as a growth multiplier its effect on the model can be inferred directly from its value.

Four new runs of the model were conducted with fullCanAge set at 3, 4, 6, and 7 years (and FR = 1) to determine the mean bias of annual biomass productivity (Mg ha^{-1} yr^{-1}) at each site and for the overall dataset, as well as RMSE for the overall dataset (Figure 7). Mean bias was calculated by summing the differences between actual and predicted annual biomass productivity, and dividing by the number of observations. For the overall dataset (pooled across all sites and ages), mean bias ranged from -1.2 (fullCanAge = 7) to 1.5 Mg ha^{-1} yr^{-1} (fullCanAge = 3), and RMSE ranged from 1.3 Mg ha^{-1} yr^{-1}

(fullCanAge = 5) to 2.0 Mg ha^{-1} yr^{-1} (fullCanAge = 3). Individual sites varied widely in their response to manipulation of the parameter; one site (MON88) achieved minimum bias at fullCanAge = 3, while two sites (ASH87 and SXF87) achieved minimum bias at fullCanAge = 7.

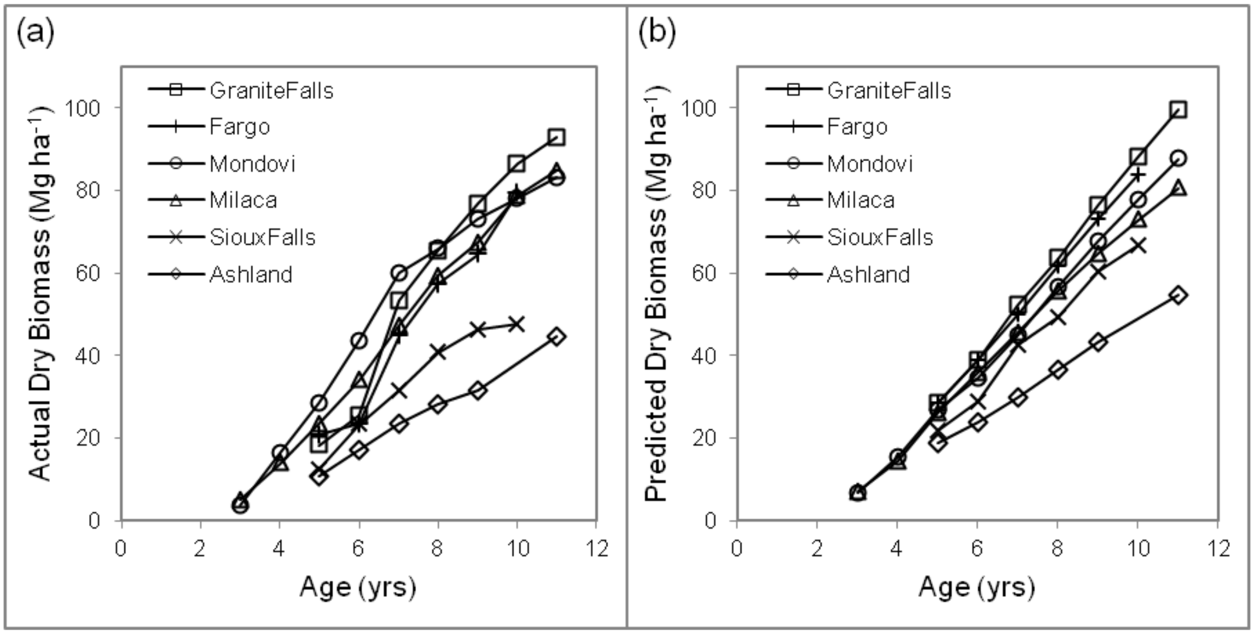


Figure 5. Actual (a) and predicted (b) biomass growth for hybrid poplar plantations established in 1987.

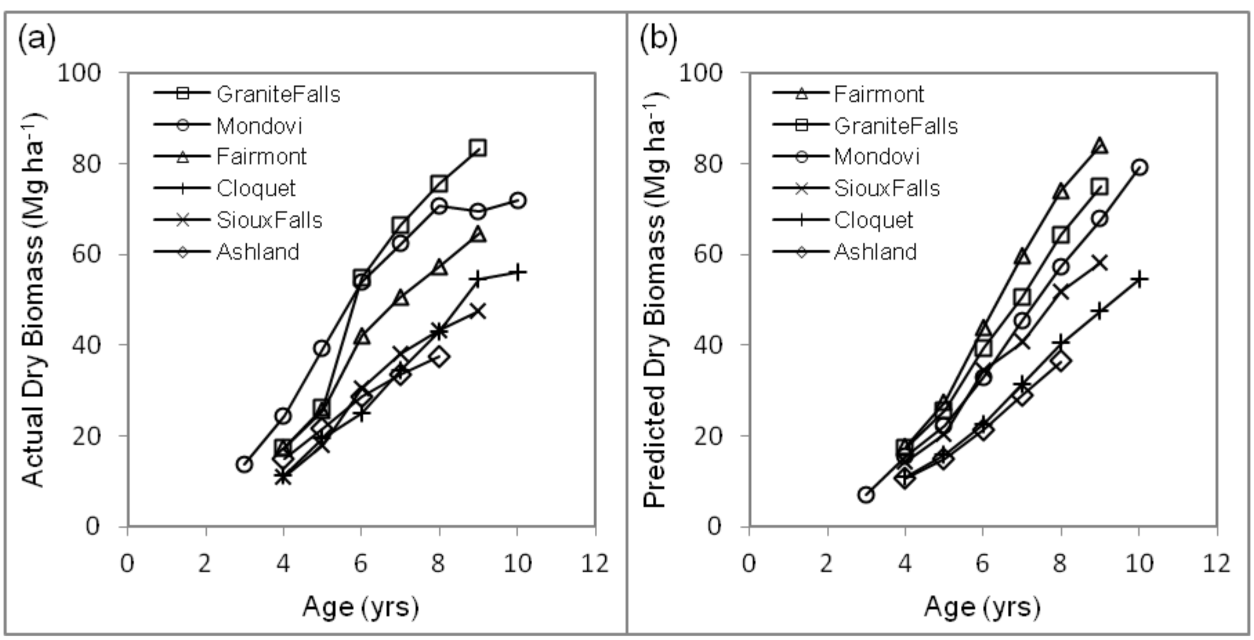


Figure 6. Actual (a) and predicted (b) biomass growth for hybrid poplar plantations established in 1988.

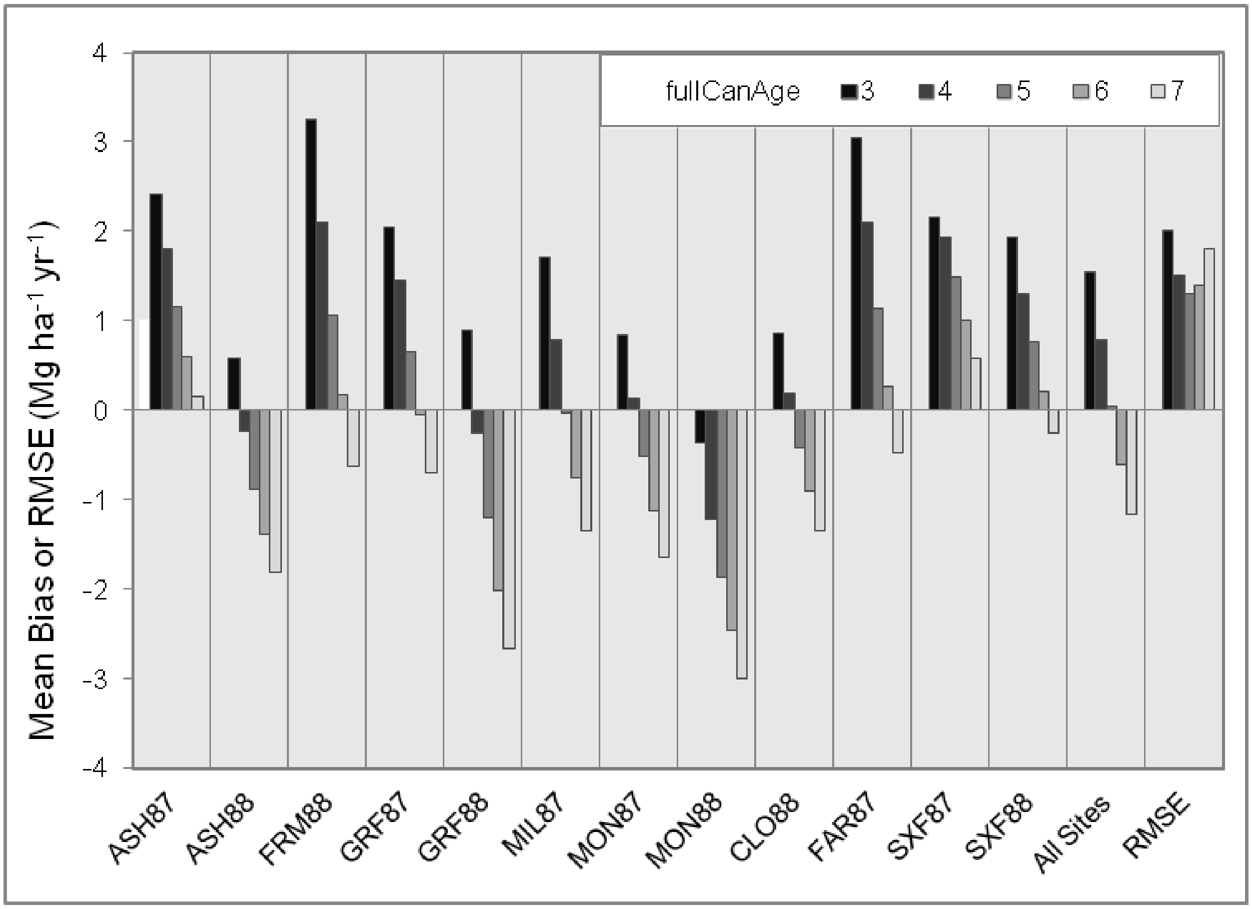


Figure 7. Sensitivity (mean bias; Mg ha^{-1} yr^{-1}) of the model by site for various levels of the full canopy age (fullCanAge) parameter, and sensitivity (mean bias and RMSE; Mg ha^{-1} yr^{-1}) of the overall model pooled across all sites.

Mapping Biomass Productivity

Once calibrated and validated for the region, 3-PG was used to model productivity across Minnesota and Wisconsin within a geographic information system (GIS; ArcGIS, ESRI, Redlands, CA). Temperature, precipitation, and solar radiation climate data (32-km resolution) were retrieved from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006) through the NOAA National Operational Model Archive and Distribution System (NOMADS) (Rutledge et al., 2006). The NARR climate data were geo-referenced with latitude and longitude coordinates that were used to attribute an ArcGIS 32-km base grid corresponding to the Lambert conformal (AWIPS) grid (Mesinger et al., 2006). The data consisted of 8 datapoints per month (each one representing a 3-hr period of the day), for each month over a 10-year period (1998-2008), giving a total of 960 observations per climate variable.

To determine whether to use 2-meter temperature or surface temperature from the NARR data, we compared both to weather station data at three locations (Fairmont, Granite Falls, and Milaca, MN) over the period 1987 to 1998. The results showed that maximum temperature is closely matched by the 2-meter data, while minimum temperature is closely matched by the surface data (Figure 2 of Appendix C); as such, this combination of temperature data was used for the remainder of the mapping process.

Average monthly values of maximum and minimum temperature were determined by averaging the maximum and minimum 3-hour temperatures, respectively, across the 10-year period. Because the NARR data is produced from separate terrestrial and water models, with cells having 50% or more area in water assigned to the water model, a number of the climate grid cells overlapping the shoreline of the Great Lakes contained temperature data which were representative of conditions over water rather than land. To provide terrestrial-based temperature data for the land area within these 23 cells (or about 5% of the total number of cells), temperature data from the next-closest cell inland were used. For average monthly precipitation, the 3-hr values of mean accumulated precipitation were summed and multiplied by the number of days in the month, and then averaged across the 10-year period. To determine average daily solar radiation for each month, the 3-hr values of mean hourly downward shortwave radiation flux were averaged for the month, then averaged across the 10-year period, and finally multiplied by 24 h d^{-1}. Soils data were retrieved through the State Soil Geographic (STATSGO2) database from the Natural Resource Conservation Service (NRCS) (NRCS, 2011). Available soil water and depth to water table for each soil map unit were obtained directly from the STATSGO2 “muaggatt” tables for Minnesota and Wisconsin. Soil texture group was determined by calculating the weighted average for clay and sand content in the component soils comprising each soil map unit. Specifically, weighted averages were calculated for clay and sand content in the top 100 cm of each component soil (based on soil horizon thickness in the “chorizon” table), which were then used to calculate weighted averages for clay and sand content in each soil map unit (based on the soil component percentages found in the “component” table). The soil map units were then assigned to soil texture groups according to Table 1.

To match the scale of the soils data (various-sized map units) to that of the climate data (32-km geo-referenced cells), soil variables were averaged (weighted by map unit area) for each soil texture group in each climate cell. Productivity was then estimated with 3-PG for each soil texture group in each cell, from which an overall average (weighted by soil texture group area) was calculated for each cell. Finally, the two-state map was created by attributing these productivity estimates to the NARR base grid described above. The resulting map of predicted biomass for Minnesota and Wisconsin is shown in Figure 8. Annual biomass productivity at age 10 ranged from 4.4 to 13.0 Mg ha^{-1} yr^{-1} across the states, with the highest productivity mainly concentrated in the area stretching from south-central Minnesota across southern Wisconsin.

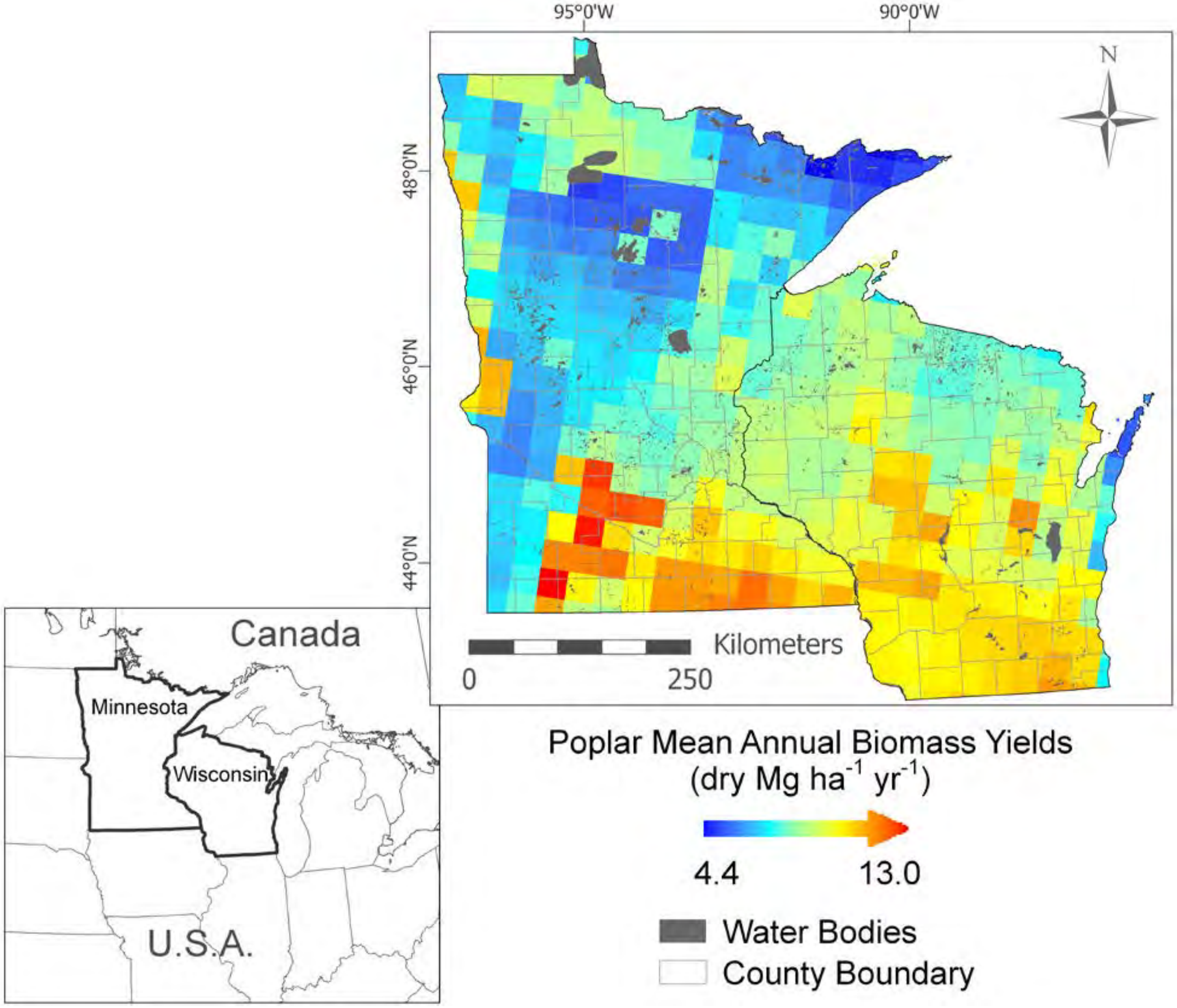


Figure 8. Map of predicted annual biomass productivity for hybrid poplars in Minnesota and Wisconsin. Predictions were generated with the calibrated 3-PG model, using data from the National Oceanic and Atmospheric Administration (NOAA) NOMADS climate database (NOAA, 2011) and Natural Resource Conservation Service (NRCS) STATSGO2 soils database (NRCS, 2011).

Objective 4: Productivity Estimates within Eligible Lands

Methods

3-PG Model Development and Productivity Mapping

In addition to identifying suitable lands, several of the climate and soil variables described above were used to estimate poplar productivity in the process-based model 3-PG (Landsberg and Waring, 1997). We used the same methods as those described in detail for Objective 3, but with SSURGO rather than STATSGO soil data; this provided similar results at the state level but greater resolution at the county level. Soil parameters used in 3-PG were retrieved from the SSURGO muaggatt data table, and included soil texture, available soil water in the top 100 cm, and minimum depth to water table (wtdepannmin). Climate variables included in the 3-PG model consisted of the 10-year monthly averages for surface precipitation, temperature, and downward shortwave radiation estimated using NARR climate data. We used the 2-meter air temperature variable to represent maximum temperature (Tmax) and surface-level NARR data to represent minimum temperature (Tmin), as these data gave the best-fit when compared to weather station data for selected sites (see Objective 3).

For all sites, a planting density of 1,736 trees per hectare and rotation age of 10 years were assumed, as well as a fertility rating (FR) = 1 and age at full canopy cover (fullCanAge) = 5 years. Three yield scenarios were tested with 3-PG; one simulating yields with generalist clones (i.e., the default settings for poplar developed in Objective 3), and two simulating yields with specialist clones with optimum temperature for growth set equal to each site's mean maximum growing season temperature from June through August. These optimum temperatures were based on the results of Drew and Chapman (1992), who reported that *P. trichocarpa*, *P. deltoides*, and their hybrids were adapted to their origin's prevailing local climatic conditions with optimal temperature for photosynthesis approximately equal to the mean maximum temperature for June through August. Of the two simulations for specialist clones, one utilized SSURGO soil texture data while the other used soil texture from field reconnaissance, to illustrate the potential impact of inaccuracies in soil data on model predictions. Analyses of variance (ANOVAs) were conducted to test for differences among the three simulations assuming a completely randomized design (SAS Institute Inc., 2004). Similarly, using the SSURGO simulation for specialist clones, productivity values were subjected to independent ANOVAs for soil texture, drainage class, slope class, and erosion risk. Fisher's protected least significant difference (LSD) was used to compare all means, which were considered different at probability values of $P < 0.05$.

To show the spatial variability in potential productivity across Minnesota and Wisconsin, we estimated potential productivity using 3-PG within each 32-km NARR climate cell. The scenario of specialist clones with SSURGO data was used for this purpose; as such, the estimates should be treated as the maximum potential yield from clones ideally matched to planting sites based on optimal temperature. To determine the potential productivity for each 32-km geo-referenced climate cell, we used area weighted averages of productivity estimated by soil texture groups and based on the area of each soil map unit (polygon) within each climate cell. Specifically, we assigned each soil map unit (polygon) to one of four soil texture groups in 3-PG (clay, clay loam, sandy loam, sand) (Table 1), and calculated weighted averages of available soil water and depth to water table for each soil group in the climate cell based on the area of the polygons. Along with the climate values for each climate cell, these soils values were used to estimate biomass productivity for each soil texture group in each climate cell using 3-PG. These soil-group estimates were then averaged (weighted by area) within each cell to produce a single estimate of productivity for each climate cell. This productivity layer was then overlaid with the eligible lands layer to show productivity estimates for those lands suitable for afforestation across the two-state area.

There were several limitations to the climate and soils source data. Because NARR uses terrestrial or water models depending on the proportion of land within each 32-km cell, cells having 50% or more water (i.e., along the shoreline of the Great Lakes) contained temperature data that were based off the water models. To provide terrestrial-based temperature data for these 23 cells (or about 5% of the total number of cells), temperature data from the next-closest inland cell was used (as in Objective 3). For the soils data, incomplete SSURGO coverage existed in a number of counties (particularly in northern Minnesota) which prevented us from estimating productivity for those areas. Such gaps may be filled in the future as SSURGO is updated, or the more generalized STATSGO soils data can be used (see Objective 3). The latter was not attempted for this study due to the prevalence of forestland and public land (both of which are excluded by our selection criteria for suitable lands) in the areas which currently lack SSURGO data.

We estimated potential productivity within Douglas County, MN, to demonstrate the applicability of our methodology at the local scale, which is of practical interest for siting poplar plantations and associated bioenergy facilities within a targeted area. Productivity was estimated for each soil map unit (polygon) using the soil and climate variables described above. If a soil polygon crossed climate cells, it was divided and productivity was estimated for each section separately using the climate cell values within which the polygon was contained. Similar to the two-state map, this productivity layer was then overlaid with the suitable lands layer to show productivity estimates for those lands suitable for afforestation at the 30-m resolution.

Results

3-PG Model Development and Productivity Mapping

Input and output data for the 3-PG modeling are found in Appendix D. Poplar biomass ranged from 9.5 ± 0.3 to 11.9 ± 0.2 Mg ha^{-1} yr^{-1} for all three yield scenarios across both states, with an overall mean of 10.0 ± 0.1 Mg ha^{-1} yr^{-1}. While there was no interaction between state and genotype group ($P = 0.5163$), predicted biomass in Wisconsin (11.2 ± 0.1 Mg ha^{-1} yr^{-1}) was significantly greater than in Minnesota (10.6 ± 0.2 Mg ha^{-1} yr^{-1}) ($P = 0.0077$). In addition, biomass of specialist genotype groups was greater than predicted for the generalists ($P < 0.0001$). Specifically, biomass predictions for specialist clones utilizing soil texture from field reconnaissance were 20% greater than their generalist counterparts, and specialists with SSURGO soil texture were 18% greater. The predicted biomass was 11.6 ± 0.2, 11.4 ± 0.2, and 9.7 ± 0.2 Mg ha^{-1} yr^{-1} for the site specialists, SSURGO specialists, and generalists, respectively.

Soil texture had the greatest influence on predicted biomass ($P = 0.0321$), while the main effect of state and the state × soil texture interaction were non-significant ($P = 0.6970$ and $P = 0.2232$, respectively). Predicted biomass ranged from 10.0 ± 0.4 (sandy loam) to 13.2 ± 0.4 Mg ha^{-1} yr^{-1} (silty clay loam) across textures, with an overall mean of 11.6 ± 0.2 Mg ha^{-1} yr^{-1} (Figure 9). Soils comprised of substantial components of silt had greater overall predicted biomass, while those with sand exhibited the least.

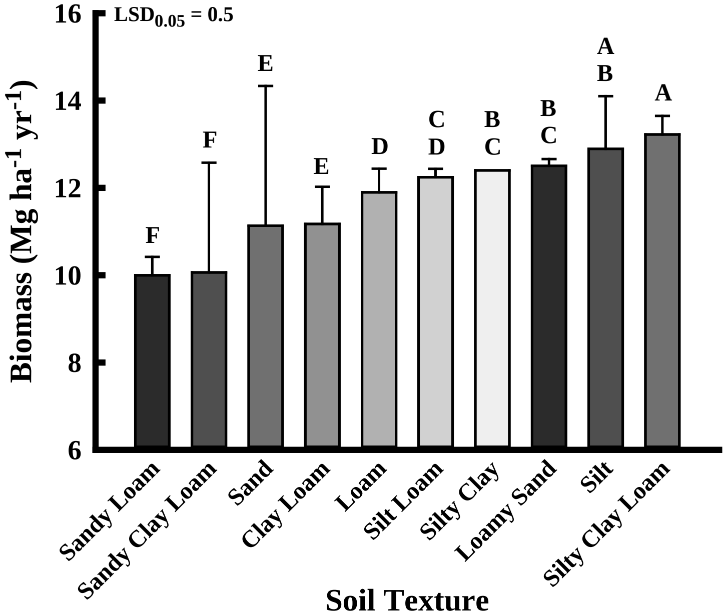


Figure 9. Predicted poplar yield on different soil textures in Minnesota and Wisconsin, USA. Standard error bars represent one standard error of the mean. Bars labeled with different letters are different according to Fisher's protected least significant difference at $P < 0.05$.

Furthermore, predicted biomass for the three remaining landscape variables was different between Minnesota and Wisconsin ($P_{\text{slope}} = 0.0241$, $P_{\text{drainage}} = 0.0105$, $P_{\text{erosion}} = 0.0298$) but was not affected by any of the independent soil classes nor their interactions with states ($P > 0.05$ for all model terms). Overall, predicted biomass in Wisconsin was 8% greater than in Minnesota. The range of biomass was relatively consistent for slope class (0.4 Mg ha^{-1} yr^{-1}) and drainage class (0.8 Mg ha^{-1} yr^{-1}), but varied most for erosion risk class (2.3 Mg ha^{-1} yr^{-1}) (Appendix E). In contrast, the predicted biomass between states was most stable for erosion risk relative to the other soil classes evaluated (Appendix F).

There was a broad range in the spatial distribution of productive lands across the study area. Lands having the greatest predicted productivity were primarily located in the northwest and southcentral regions of Minnesota, and the center and most southeastern regions of Wisconsin. However, relatively high productivity occurred throughout the southern third of Wisconsin. All of these areas are dominated by cultivated crops interspersed with pasture/hay, and have relatively richer soils. The regions with the lowest productivity were the southwestern and central regions of Minnesota. Much of this area is currently used for cultivated crops as well, but pasture/hay lands are more common.

Objective 5: Poplar Database

In addition to extensive consultations with regional and national collaborators, we compiled information by collecting information from the published poplar literature. In the process, we developed a bibliography of North American poplar research published from 1989 to 2011. The first comprehensive poplar bibliography reported literature published from 1854 to 1963 (Farmer and McNight, 1967), the second from 1964 to 1974 (Hart, 1976), and the last from 1975 to 1988 (Ostry and Henderson, 1990). Given that these bibliographies are outdated, the number of forestry/bioenergy related journals has increased dramatically (along with subsequent publications), and there have been profound advances in science (particularly in the areas of genetics and molecular biology) within the last two decades, development of the current bibliography was necessary. In addition to compiling the information into one interactive location, our objectives were to encourage publication in peer-reviewed journals and to enhance collaborations with partners outside the poplar community (i.e., to provide them with easily-accesible poplar information).

Four primary constraints were considered when including literature in the bibliography. The papers had to be *peer-reviewed (1)* and they had to contain information about poplars, cottonwoods, aspens, and their hybrids grown as *short rotation woody crops (2)* in *North America (3)*, and be pertinent to *at least one topic area (4)*. The topic areas are: cell and tissue culture, conservation, diseases, economics and social science, general, genetics, global change, growth and productivity, insects and mites, physiology, phytotechnologies, silviculture, and wood science and wood products. The bibliography contains 862 unique citations that are cross-listed among up to three topic areas, resulting in 1,398 total entries. The number of citations within each topic area is shown to the right.

Topic Area	Citations
Physiology	273
Genetics	254
Growth and Productivity	200
Silviculture	130
Phytotechnologies	123
Insects and Mites	77
Diseases	76
Conservation	65
General	50
Wood Science and Wood Products	49
Global Change	38
Economics and Social Science	36
Cell and Tissue Culture	27

**Farmer, RE Jr., McKnight, JS. 1967. (1854 to 1963) USDA FS SO-RP-27. 132 p.*
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Discussion

Productivity Model Development

As parameterized and calibrated in this study, 3-PG appears well-suited for modeling poplar biomass productivity in Minnesota and Wisconsin. Linear regression of actual versus predicted biomass for the validation dataset demonstrated a strong fit (R^2 = 0.89, RMSE = 8.1; see Figure 4). Individually, few sites deviated significantly from the overall model with regard to slope and intercept for actual versus predicted biomass (see Figure 1 of Appendix C), and the model was able to separate higher productivity sites from lower productivity sites (see Figures 5 and 6). When used to map productivity across Minnesota and Wisconsin (see Figure 8), mean annual biomass predictions and their spatial trends were consistent with previous research. Specifically, the range of biomass estimates (4.4 to 13.0 Mg ha^{-1} yr^{-1}) is consistent with that observed for DN34 (4.80 to 9.01 Mg ha^{-1} yr^{-1}; ages 7 to 10 years) at sites in Minnesota and Wisconsin reported by Zalesny et al. (2009), and the overall spatial trend is consistent with that projected for poplars in the Oak Ridge Energy Crop County Level (ORECCL) database (Graham et al., 1996). Interestingly, biomass is predicted to be highest along the boundary between high and low productivity in southern Minnesota; this appears to stem from the shallow water tables derived from the STATSGO2 soils data, along with the somewhat higher solar radiation and temperatures derived from the NARR climate data.

The model was sensitive to manipulation of the fullCanAge parameter; a change of 2 years in either direction produced a mean bias (averaged across all sites and ages) of 1.2 to 1.5 Mg ha^{-1} yr^{-1}, and the value of fullCanAge which produced the most accurate results varied by site (see Figure 7). Notably, all of the sites having significantly different slopes and intercepts from the overall model (FAR87, FRM88, GRF87, and MON88; see Figure 1 of Appendix C) achieved minimum bias at fullCanAge values other than 5. In addition, plantations established in 1987 generally achieved minimum bias at higher values of fullCanAge, while those established in 1988 generally achieved minimum bias at lower values of fullCanAge. This may be related to more favorable establishment conditions (relating to weather conditions, site preparation, and/or weed control) for the 1988 plantations.

It should also be noted that fullCanAge and FR are almost certainly related, to the extent that higher fertility is associated with faster growth and therefore earlier canopy closure. By optimizing fit for the individual sites, we hypothesize that the true values of FR range from 0.85 to 1, with fullCanAge ranging from 3 to 6 years and negatively correlated with FR (Table 7 of Appendix C). These site-specific estimates of FR and fullCanAge improve the overall model fit (R^2 = 0.95, RMSE = 5.4 Mg ha^{-1}) but require prior knowledge of yields and therefore cannot be validated here. To this end, methods for reliably measuring FR and predicting fullCanAge for individual sites without prior knowledge of yields should be further investigated.

More accurate predictions of biomass productivity may also be possible with more specific knowledge of physiological parameters (i.e. clone-specific values rather than those for parent species or related clones), and/or a more complete accounting of damaging agents (i.e. disease, insects, weed competition, and extreme weather events). For example, the model consistently overpredicted biomass at several sites (FRM88, SXF87, and SXF88) which were among the most severely affected by stem canker as rated by Netzer et al. (2002); however, their rating system did not quantify yield reductions associated with the canker, which precluded us from attempting to account for it in the model. Such damaging agents are likely to interact with fullCanAge, to the extent that they result in a loss or slowing of growth that in turn may delay canopy closure. In practical terms, these damaging agents can be accounted for by adjusting fullCanAge alone (for one-time events such as ice storms) or along with FR (for annually-repeating events such as disease), where FR becomes a metric for the combined effects of site fertility and the damaging agent.

Even though coefficients for other tree growth variables (i.e. DBH, height, volume, self-thinning) were obtained from the literature, the model was only calibrated and validated in this study for aboveground biomass. Additional work should be done to validate model outputs for these other growth variables. Also, it is important to reiterate that the model was only calibrated and validated for the clones DN17, DN34, and DN182 reported in Netzer et al. (2002). Other clones may have different parameter values (e.g. optimum temperature, minimum and maximum fraction of NPP to roots, etc), and therefore more work should be done to parameterize and calibrate the model for a wider selection of clones used in the region. Similarly, further work should be done to adapt the model to other regions. Because different clones are more commonly utilized in other regions, the model should be re-calibrated for these clones (or groups of clones), especially when they are not closely related to the ones considered here. While the physiological parameters and allometric relationships likely apply equally well in other regions for these particular clones, other values (or ranges of values) are likely to occur for variables such as FR. In addition, the most suitable cutoff for depth to water table in the ASW_{min} equation may also vary by region.

Finally, due to the coarse scale of the biomass productivity map, it should not be used for siting poplar plantations at local (e.g. individual landowner) scales. Rather, the map is intended to be useful at the regional scale (e.g. county or multi-county scale) to compare average productivity in different areas where bioenergy facilities may be placed. Within such areas, finer-scale site input data (particularly for soils) may be used to generate local-level biomass estimates, which may vary considerably around the averages depicted in the coarse-scale map. In addition, non-biological factors (such as land ownership and current land use) place constraints on poplar deployment which are not considered here. Additional work was conducted to evaluate the potential of using 3-PG to predict and map biomass yields at finer scales, with consideration for such constraints [see next section].

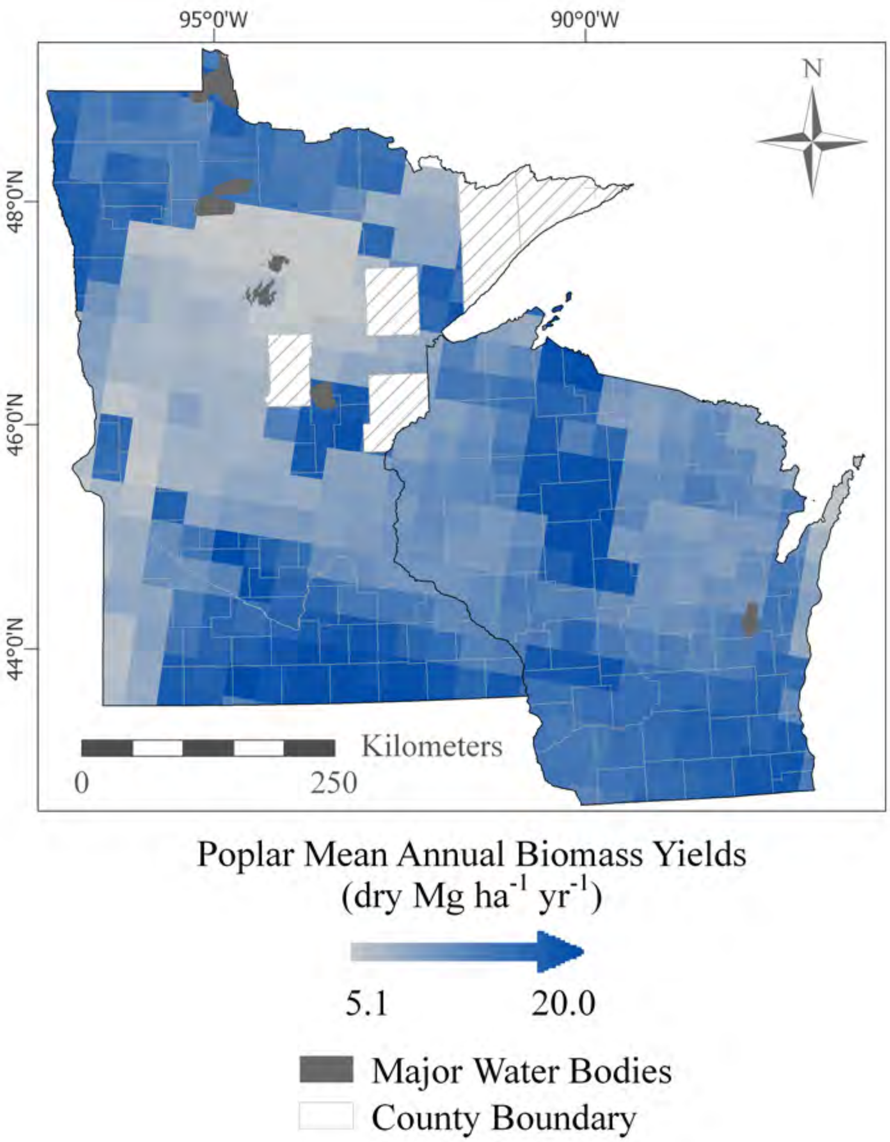
Mapping, Field Reconnaissance, and Productivity within Eligible Lands

A critical component of promoting and growing IMPPs is the identification of lands that are suitable for these feedstock production systems (Husain et al., 1998). The 3-PG model and our validation techniques are widely adaptable to other woody crops across North America and worldwide, and our data indicate that it is possible to predict, with relative accuracy, both the area and location of lands that could support IMPPs. While coarse estimates of land suitable for IMPPs exist (Alig et al, 2000), our approach links the locations of eligible lands with their potential productivity. Such information can be combined with economic analyses and socioeconomic factors to accurately and effectively determine where IMPPs would have the best chance of success (Malczewski, 2004).

In general, the spatial distribution of lands suitable for IMPPs followed land ownership and land use/cover patterns, while modeled productivity within these lands followed soil texture patterns, which was not surprising given the potential importance of soil characteristics in 3-PG modeling results (Dye et al., 2004). Productivity estimates for the specific field sites were significantly influenced by soil texture (Figure 9), but were not significantly affected by the other variables evaluated (drainage class, slope class, and erosion risk; Appendix E), likely because soil texture is an input variable for 3-PG, but the other variables are only accounted for indirectly to the extent that they are associated with input variables like soil texture. For example, the relatively small yield reductions predicted for the higher slope (5 to 30%) and erosion risk classes (High to Very High) may be explained by coarser textures associated with eroded hillsides; however, the model does not account for the increase in runoff and reduction in infiltration which also occurs on steep slopes, which is likely to further reduce yields. Similarly, texture may explain the predicted yield reductions for Poorly Drained (clayey) and Rapidly Drained (sandy) soils; but, the model does not account for additional factors such as anoxic conditions (Poorly Drained clays) and low CEC (Rapidly Drained sands), which are likely to further reduce yields. Theoretically, the effects of slope and/or erosion class on rain infiltration can be accounted for by reducing the precipitation input for the model, and the model's fertility rating can be used to account for anoxic or low-CEC conditions; however, such methods require further investigation and are beyond the scope of this study.

Productivity estimates (Figure 10; Figure 11) were similar to those generated in Objective 3, with the primary difference being an overall increase in yields associated with the specialist scenario used in the current study. The current use of SSURGO soils data produced a similar pattern to the STATSGO soils data (Objective 3), with the higher-productivity areas occurring in south-central Minnesota and southern Wisconsin, and the lower-productivity areas running from southwestern to northeastern Minnesota. The high productivity areas of northwest Minnesota may be influenced by temperature (Figure 2B) and the high productivity areas in central Wisconsin may be a result of greater precipitation patterns in those areas (Figure 2A), which shows the importance of considering macroscale climate influences as well as local-scale site characteristics on productivity. However, while temperature and precipitation gradients largely explain these patterns, it should also be noted that some of the highest predicted yields are in relatively low-precipitation areas. These areas tend to have shallow water tables which mitigate low rainfall in the model; they also tend to have higher growing season temperatures and solar radiation, which further increases the model's yield predictions.

Figure 10. Predicted poplar yield across Minnesota and Wisconsin, USA, assuming SSURGO soils data and specialist genotypes that are matched to ideal site conditions. Productivity is shown at 32 × 32 km resolution. Due to lack of soil spatial data, it was not possible to predict productivity within the gray hatched areas.



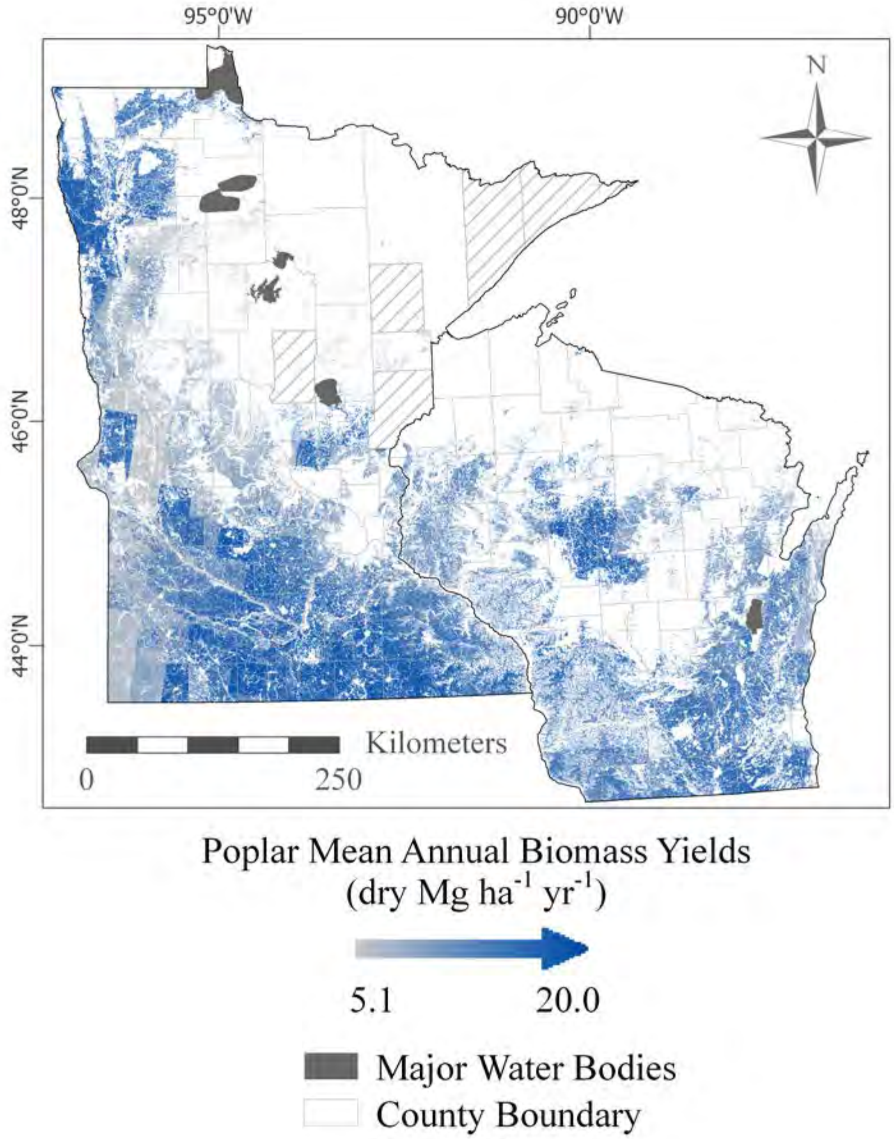


Figure 11. Predicted poplar yield within the suitable land base, assuming SSURGO soils data and specialist genotypes that are matched to ideal site conditions. Productivity is shown at 32 × 32 km resolution. Due to lack of soil spatial data, it was not possible to predict productivity within the gray hatched areas.

The effects of water table access are also illustrated in the productivity map for Douglas County (Figure 12). In general, the areas with predicted yields greater than 10 Mg ha^{-1} yr^{-1} have water tables that reach within the top meter of soil, whereas the areas with predicted yields lower than 10 Mg ha^{-1} yr^{-1} have water tables that stay below the top meter. Linear regression of the data confirmed that predicted yield has a strong, negative relationship with depth to water table ($R^2 = 0.86$) in Douglas County. However, water table depth is unlikely to have as strong an effect on predicted yields in counties having higher precipitation.

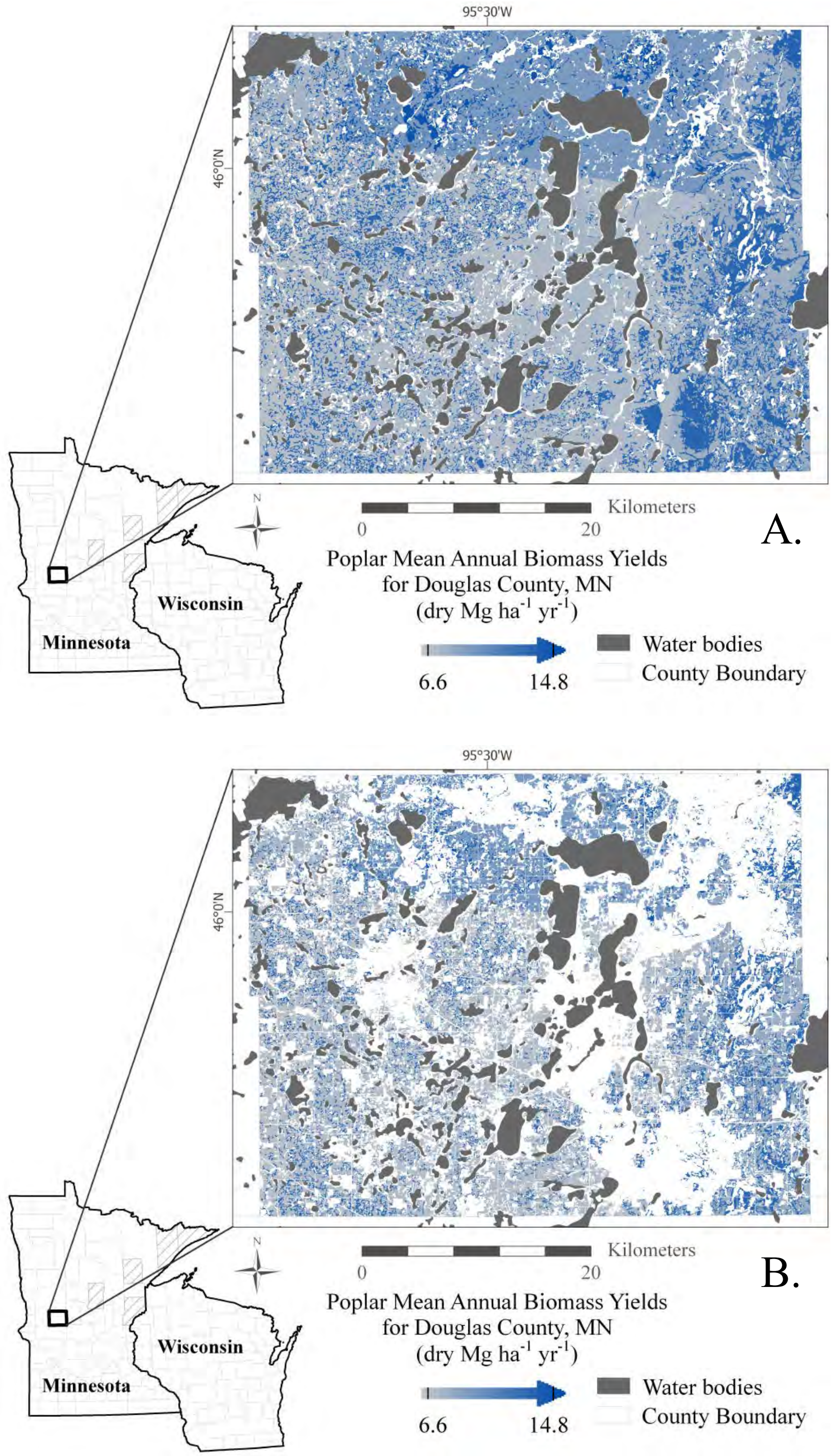


Figure 12. Predicted poplar yield throughout (A.) and on suitable lands within (B.) Douglas County, Minnesota, USA, assuming SSURGO soils data and specialist genotypes that are matched to site conditions. Productivity is shown at 30 × 30 m resolution.

Given our results, land conversion may be expected to occur in those areas with high estimated productivity. However, much of these lands are currently being used for cultivated crops, and the economic return of IMPPs will have to be evaluated compared to returns from agricultural crops (Updegraff et al., 2004). Of particular note is the location of some of the current IMPPs in Minnesota (Figure 1), which are located in relatively low productivity areas such as in Douglas County. These lands may not be as desirable for cultivated crops as those in southern portions of the state, which may actually make them more economically attractive to convert to IMPPs due to lower competition for the landbase. Poplar crop enterprise budgets are still in development, nevertheless, it is worth noting that we attempted to incorporate two key socioeconomic variables into the modeling process while defining suitable lands: 1) land rental rates (USDA Farm Service Agency) and 2) corn yield by county (National Agriculture Statistics Service). However, large-scale spatial data was either not available or not reported in a consistent county-by-county manner, and so we excluded both from consideration for our final constraints. Incorporating socioeconomic variables at the finer-scale such as for Douglas County could help to further refine our results for those areas of interest.

Water availability and soil quality contribute to poplar site suitability (Thornton et al., 1998; Perry et al., 2001), as these woody crops often require large amounts of water and soil nutrients to maximize productivity (Updegraff et al., 1990; Gochis and Cuenca, 2000). Water availability was an important model component in this study, and is often directly related to poplar productivity (Souch and Stephens, 1998; Coyle and Coleman, 2005; Bergante et al., 2010). Likewise, soil texture and nutrient availability can have dramatic impacts on poplar productivity (Fang et al., 2008; Hancock et al., 2008; Pinno et al., 2010). Predicted poplar productivity in this study was greatest on lands with a combination of adequate water availability and healthy soils, both in texture and nutrition (Figure 10). Not surprisingly, these attributes are part of what make Minnesota and Wisconsin such agriculturally productive states.

In addition to these general trends, it is necessary to assess the advantages of matching specific genotypes with climate and soil variables at potential areas of establishment. The genus *Populus* exhibits an extensive amount of genetic variability (Rajora and Zsuffa, 1990; Eckenwalder, 1996), which can be exploited for the purposes of enhancing the feasibility of promoting and growing IMPPs. For example, the specialist and generalist genotype scenarios in the current study were modeled to determine the potential advantage of maximizing the productivity benefits of genotype × environment interactions versus maintaining the status quo across the landscape. In general, the specialists exhibited 20% greater productivity than the generalists (range equal to 3% to 58%), which was a similar trend of lower magnitude relative to other reports in the Midwestern United States. Zalesny et al. (2009) reported the biomass of the top six specialist clones was 130% greater than the biomass of generalist clones throughout Minnesota, Wisconsin, and Iowa at 7 to 10 years after planting. Similarly, Riemenschneider et al. (2001) reported a 50% advantage for the five best clones at six years after planting across these states. The primary potential reason for the lower advantage of specialists versus generalists in the current study compared with those previously reported is that specialist scenarios modeled here only simulate improvements in adaptation to local temperature regimes. Additional genetic improvements such as root biomass allocation rates that are optimally suited to site conditions likely contribute to the higher yields of specialist clones in the literature. Such improvements may be simulated in 3-PG, but would require development of a reliable estimator of "optimal" root biomass allocation based on site-specific soil

and climate factors; further efforts to this end are warranted, but are beyond the scope of this study. Nevertheless, the importance of considering both genotype groups is evident, especially when considering the climatic gradients described above. In lieu of knowledge about optimal root biomass allocation rates, known drought resistance of certain poplar genomic groups exists (Harvey and van den Driessche, 1997; Tschaplinski et al., 1998; Harvey and van den Driessche, 1999) and can be exploited given the use of our integrated approach and proper clonal selection.

The potential environmental effects of establishing region-wide IMPPs can also be reduced when matching genotypes to specific site conditions. Poplars can be one of the most sustainable biomass production systems, provided that the IMPPs are designed and established to conserve soil and water, recycle nutrients, and maintain genetic diversity (Hall, 2008). In general, afforestation with IMPPs has been beneficial relative to agronomic alternatives for the sustainability of parameters such as soil carbon (Coleman et al., 2004) and erosion/water quality (Joslin and Schoenholtz, 1997; Thornton et al., 1998), while being neutral for factors such as greenhouse gas emissions during establishment (Saurette et al., 2008). Achieving these ecosystem services is paramount for the success of future IMPPs, which is especially important for landowners and resource managers making decisions on balancing their costs and financial returns with environmental sustainability goals. Overall, integrating large-scale biophysical spatial data and local site information with 3-PG growth modeling was an effective means of assessing where IMPPs can be established throughout Minnesota and Wisconsin, and we hope this approach will contribute to woody biomass feedstock production that can be used to offset electricity generation and natural gas use in the region.

Conclusions

Development and selection of appropriate energy crops lags behind anticipated need in most regions of the United States, especially the Midwest. Establishing poplar genotypes that are adapted to local environmental conditions substantially increases plantation success, subsequent productivity, and the ability of the trees to contribute to soil and water quality, nutrient recycling, and carbon sequestration. Failure to match proper genotypes with sites of deployment may curtail potential economic and environmental benefits associated with the dedicated poplar energy crops. Furthermore, success of these plantations and subsequent production of electricity and thermal energy using woody biomass can be used to offset electricity generation and natural gas use in Wisconsin, Minnesota, and other states. Recognizing this potential, modular biomass power plant systems are currently an energy option. These systems are especially attractive for isolated communities or where excess thermal energy can be used in commercial situations. However, these systems require a constant source of woody biomass, which must be obtained within a fairly small radius to be economically feasible during the transportation process. It is questionable whether the surrounding forests will be able to provide this biomass on a long-term sustainable basis. Using poplar feedstock to supplement required biomass requirements could reduce the impacts of obtaining woody biomass from the surrounding natural environments.

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Appendix A: Site Information

See Table 2 for definitions of drainage and erosion risk classes.

Site	State	County	Lat (°N)	Long (°W)	Site type	Current vegetation	Slope	Drainage class	Erosion risk class
MN1	Minnesota	Chisago	45.5	92.7	Agronomic	Soybeans	0-2%	Imperfectly Drained	Medium
MN2	Minnesota	Chisago	45.4	92.7	Agronomic	Corn / Woodlot	0-2%	Imperfectly Drained	Medium
MN3	Minnesota	Chisago	45.7	92.9	Agronomic	Alfalfa	0-2%	Imperfectly Drained	Low
MN4	Minnesota	Chisago	45.7	93.1	Agronomic	Grass	2-5%	Well Drained	Very Low
MN5	Minnesota	Mille Lacs	45.8	93.6	Old Poplar Trial	Poplar	2-5%	Moderately Well Drained	Very Low
MN6	Minnesota	Benton	45.7	93.9	Agronomic	Alfalfa / Shrub / Corn	0-2%	Poorly Drained	Very Low
MN7	Minnesota	Morrison	45.9	94.1	Agronomic	Corn / Grass	2-5%	Imperfectly Drained	Medium
MN8	Minnesota	Wadena	46.4	94.9	Poplar Production	Poplar	0-2%	Moderately Well Drained	Very Low
MN9	Minnesota	Wadena	46.4	94.9	Poplar Production	Poplar / Grass	0-2%	Poorly Drained	Very Low
MN10	Minnesota	Wadena	46.5	94.9	Agronomic	Grass / Potato	2-5%	Well Drained	High
MN11	Minnesota	Becker	46.9	95.3	Agronomic	Aspen Forest	5-9%	Rapidly Drained	Very Low
MN12	Minnesota	Becker	47.0	95.4	Agronomic	Grass	0-2%	Well Drained	Low
MN13	Minnesota	Becker	47.1	96.2	Old Poplar Trial	Poplar	2-5%	Imperfectly Drained	Very Low
MN14	Minnesota	Becker	47.1	96.2	Old Poplar Trial	Poplar	2-5%	Moderately Well Drained	Very Low
MN15	Minnesota	Norman	47.4	96.3	Poplar Production	Poplar	0-2%	Well Drained	Very Low
MN16	Minnesota	Norman	47.4	96.1	Agronomic	Soybeans	0-2%	Poorly Drained	High
MN17	Minnesota	Norman	47.5	96.2	Agronomic	Alfalfa / Corn	0-2%	Moderately Well Drained	Low
MN18	Minnesota	Polk	47.7	96.0	Poplar Production	Poplar	0-2%	Moderately Well Drained	Very Low
MN19	Minnesota	Red Lake	47.8	95.9	Poplar Production	Poplar	0-2%	Well Drained	Very Low
MN20	Minnesota	Red Lake	47.9	96.0	Poplar Production	Poplar	0-2%	Imperfectly Drained	Very Low
MN21	Minnesota	Pennington	48.0	96.0	Poplar Production	Poplar	0-2%	Well Drained	Very Low
MN22	Minnesota	Roseau	48.7	96.3	Agronomic	Wheat	0-2%	Imperfectly Drained	Medium
MN23	Minnesota	Roseau	48.8	95.8	Agronomic	Sod Farm	0-2%	Well Drained	Very Low
MN24	Minnesota	Kittson	48.7	96.8	Agronomic	Sugar Beet	0-2%	Moderately Well Drained	High
MN25	Minnesota	Marshall	48.5	96.8	Agronomic	Sugar Beet	0-2%	Imperfectly Drained	High
MN26	Minnesota	Marshall	48.2	96.7	Agronomic	Grass (Fallow Field)	0-2%	Well Drained	Very Low
MN27	Minnesota	Norman	47.3	96.7	Agronomic	Soybeans	0-2%	Well Drained	Medium
MN28	Minnesota	Clay	46.9	96.5	Agronomic	Soybeans / Wheat	0-2%	Imperfectly Drained	High
MN29	Minnesota	Wilkin	46.5	96.5	Agronomic	Sugar Beet	0-2%	Well Drained	Medium
MN30	Minnesota	Wilkin	46.1	96.4	Agronomic	Tilled Field	0-2%	Moderately Well Drained	Very High
MN31	Minnesota	Traverse	45.9	96.4	Agronomic	Corn	0-2%	Imperfectly Drained	Very High
MN32	Minnesota	Stevens	45.6	96.2	Agronomic	Corn	0-2%	Well Drained	High
MN33	Minnesota	Douglas	46.1	95.1	Poplar Production	Poplar	0-2%	Well Drained	Very Low
MN34	Minnesota	Todd	46.3	95.0	Poplar Production	Poplar	5-9%	Moderately Well Drained	Very Low
MN35	Minnesota	Otter Tail	46.2	95.2	Poplar Production	Poplar	2-5%	Rapidly Drained	Very Low
MN36	Minnesota	Otter Tail	46.1	95.1	Poplar Production	Poplar	5-9%	Well Drained	Low

Appendix A: Site Information

See Table 2 for definitions of drainage and erosion risk classes.

Site	State	County	Lat (°N)	Long (°W)	Site type	Current vegetation	Slope	Drainage class	Erosion risk class
MN37	Minnesota	Otter Tail	46.5	95.4	Poplar Production	Poplar	0-2%	Well Drained	Low
MN38	Minnesota	Red Lake	47.8	95.9	Poplar Production	Poplar	0-2%	Imperfectly Drained	Low
MN39	Minnesota	Clearwater	47.7	95.4	Old Poplar Trial	Poplar	2-5%	Well Drained	Very Low
MN40	Minnesota	Beltrami	47.7	95.1	Poplar Production	Poplar	5-9%	Moderately Well Drained	Very High
MN41	Minnesota	Clearwater	47.4	95.2	Poplar Production	Poplar	5-9%	Well Drained	Very High
MN42	Minnesota	Stearns	45.7	94.7	Agronomic	Oats / Alfalfa	5-9%	Moderately Well Drained	Low
MN43	Minnesota	Pope	45.7	95.2	Agronomic	Corn / Grass	0-2%	Well Drained	Low
MN44	Minnesota	Stearns	45.7	95.1	Old Poplar Trial	Poplar	0-2%	Well Drained	Very Low
MN45	Minnesota	Wright	45.0	94.1	Agronomic	Oats	2-5%	Well Drained	Very High
MN46	Minnesota	Rice	44.4	93.3	Agronomic	Corn / Grass	5-9%	Moderately Well Drained	Low
MN47	Minnesota	Goodhue	44.6	92.8	Agronomic	Corn	0-2%	Moderately Well Drained	Very High
MN48	Minnesota	Nicollet	44.4	94.1	Agronomic	Soybeans / Corn	2-5%	Moderately Well Drained	Medium
MN49	Minnesota	McLeod	44.7	94.5	Agronomic	Alfalfa / Ditch	2-5%	Moderately Well Drained	Very Low
MN50	Minnesota	Kandiyohi	44.9	94.8	Agronomic	Corn	0-2%	Imperfectly Drained	Medium
MN51	Minnesota	Kandiyohi	45.0	95.2	Agronomic	Corn	2-5%	Imperfectly Drained	Medium
MN52	Minnesota	Chippewa	44.8	95.5	Old Poplar Trial	Poplar	0-2%	Poorly Drained	Very Low
MN53	Minnesota	Chippewa	44.8	95.5	Old Poplar Trial	Poplar	9-15%	Poorly Drained	Very Low
MN54	Minnesota	Chippewa	45.1	95.7	Agronomic	Soybeans	0-2%	Imperfectly Drained	High
MN55	Minnesota	Yellow Medicine	44.8	96.2	Agronomic	Tillage Radish	2-5%	Moderately Well Drained	Medium
MN56	Minnesota	Lyon	44.5	95.8	Agronomic	Corn	2-5%	Imperfectly Drained	High
MN57	Minnesota	Yellow Medicine	44.6	95.4	Agronomic	Sunflower	2-5%	Moderately Well Drained	Low
MN58	Minnesota	Redwood	44.5	95.0	Old Poplar Trial	Poplar	0-2%	Moderately Well Drained	Very Low
MN59	Minnesota	Redwood	44.2	95.3	Old Poplar Trial	Poplar	2-5%	Well Drained	Very Low
MN60	Minnesota	Cottonwood	44.0	95.0	Agronomic	Corn	0-2%	Moderately Well Drained	Medium
MN61	Minnesota	Nobles	43.7	95.5	Agronomic	Soybeans	0-2%	Moderately Well Drained	High
MN62	Minnesota	Nobles	43.7	95.9	Agronomic	Grass	2-5%	Moderately Well Drained	Very Low
MN63	Minnesota	Pipestone	43.9	96.3	Agronomic	Soybeans	0-2%	Moderately Well Drained	Medium
MN64	Minnesota	Rock	43.5	96.4	Agronomic	Corn	2-5%	Imperfectly Drained	Medium
MN65	Minnesota	Martin	43.7	94.3	Old Poplar Trial	Poplar	5-9%	Moderately Well Drained	Very Low
MN66	Minnesota	Le Sueur	44.3	93.6	Agronomic	Corn	5-9%	Imperfectly Drained	High
MN67	Minnesota	Waseca	44.1	93.5	Old Poplar Trial	Poplar	2-5%	Well Drained	Very Low
MN68	Minnesota	Freeborn	43.8	93.5	Agronomic	Soybeans	5-9%	Moderately Well Drained	Medium
MN69	Minnesota	Freeborn	43.6	93.3	Agronomic	Alfalfa	0-2%	Moderately Well Drained	Very Low
MN70	Minnesota	Mower	43.5	92.9	Agronomic	Soybeans	0-2%	Moderately Well Drained	Medium
MN71	Minnesota	Dodge	43.9	92.9	Agronomic	Grass / Corn	0-2%	Moderately Well Drained	Medium
MN72	Minnesota	Olmsted	44.2	92.4	Agronomic	Corn	9-15%	Imperfectly Drained	High

Appendix A: Site Information

See Table 2 for definitions of drainage and erosion risk classes.

Site	State	County	Lat (°N)	Long (°W)	Site type	Current vegetation	Slope	Drainage class	Erosion risk class
MN73	Minnesota	Olmsted	43.9	92.4	Agronomic	Soybeans	2-5%	Imperfectly Drained	Medium
MN74	Minnesota	Winona	43.9	91.7	Agronomic	Alfalfa	9-15%	Well Drained	Very High
MN75	Minnesota	Fillmore	43.6	91.8	Agronomic	Corn	5-9%	Moderately Well Drained	Medium
MN76	Minnesota	Beltrami	47.6	94.9	Old Poplar Trial	Poplar	2-5%	Well Drained	Very Low
MN77	Minnesota	Polk	48.1	96.7	Old Poplar Trial	Poplar	0-2%	Moderately Well Drained	Low
MN78	Minnesota	Otter Tail	46.3	95.6	Old Poplar Trial	Poplar	2-5%	Well Drained	Low
MN79	Minnesota	Todd	46.0	94.9	Old Poplar Trial	Poplar	2-5%	Well Drained	Low
MN80	Minnesota	Douglas	45.9	95.3	Old Poplar Trial	Poplar	2-5%	Moderately Well Drained	Very Low
MN81	Minnesota	Douglas	46.0	95.5	Old Poplar Trial	Poplar (coppice)	9-15%	Moderately Well Drained	Very High
MN82	Minnesota	Douglas	45.9	95.7	Old Poplar Trial	Poplar (coppice)	5-9%	Imperfectly Drained	Medium
MN83	Minnesota	Douglas	45.8	95.6	Old Poplar Trial	Poplar (young)	5-9%	Moderately Well Drained	High
MN84	Minnesota	Pope	45.6	95.4	Old Poplar Trial	Tilled Field	2-5%	Moderately Well Drained	Low
WI1	Wisconsin	Dane	43.3	89.4	Old Poplar Trial	Poplar (15-20 yo)	2-5%	Well Drained	Very Low
WI2	Wisconsin	Columbia	43.3	89.2	Agronomic	Soybean	2-5%	Well Drained	Low
WI3	Wisconsin	Columbia	43.4	89.1	Agronomic	Corn	2-5%	Imperfectly Drained	Medium
WI4	Wisconsin	Oneida	45.6	89.5	Old Poplar Trial	Poplar (hybrid)	2-5%	Rapidly Drained	High
WI5	Wisconsin	Oneida	45.7	89.6	Old Poplar Trial	Poplar	2-5%	Well Drained	Low
WI6	Wisconsin	Ashland	46.4	90.8	Agronomic	Young aspen/conifer	2-5%	Moderately Well Drained	Low
WI7	Wisconsin	Ashland	46.4	90.9	Agronomic	Agronomic	2-5%	Well Drained	Low
WI8	Wisconsin	Marathon	45.0	90.1	Agronomic	Corn	2-5%	Rapidly Drained	Very Low
WI9	Wisconsin	Clark	44.9	90.4	Agronomic	Corn	5-9%	Rapidly Drained	Low
WI10	Wisconsin	Clark	44.9	90.6	Agronomic	Soybean	2-5%	Well Drained	Low
WI11	Wisconsin	Chippewa	45.0	91.0	Agronomic	Corn	5-9%	Moderately Well Drained	Low
WI12	Wisconsin	Rusk	45.3	91.0	Agronomic	Hay	5-9%	Well Drained	Low
WI13	Wisconsin	Rusk	45.5	90.9	Agronomic	Hay	2-5%	Well Drained	Low
WI14	Wisconsin	Price	45.7	90.3	Agronomic	Hay	5-9%	Well Drained	Low
WI15	Wisconsin	Price	45.6	90.4	Agronomic	Hay	2-5%	Well Drained	Low
WI16	Wisconsin	Portage	44.6	89.6	Agronomic	Hay	2-5%	Well Drained	Low
WI17	Wisconsin	Portage	44.4	89.4	Agronomic	Corn	0-2%	Well Drained	Low
WI18	Wisconsin	Langlade	45.1	89.3	Agronomic	Potato	0-2%	Well Drained	Medium
WI19	Wisconsin	Langlade	45.2	89.1	Agronomic	Hay	2-5%	Well Drained	Medium
WI20	Wisconsin	Chippewa	45.0	91.5	Agronomic	Soybean	5-9%	Well Drained	Low
WI21	Wisconsin	Chippewa	45.1	91.5	Agronomic	Soybean	5-9%	Well Drained	Low
WI22	Wisconsin	Barron	45.5	91.9	Agronomic	Hay	5-9%	Moderately Well Drained	Low
WI23	Wisconsin	Barron	45.6	91.7	Agronomic	Corn	2-5%	Well Drained	Low
WI24	Wisconsin	St. Croix	45.0	92.4	Agronomic	Corn	5-9%	Well Drained	Low

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See Table 2 for definitions of drainage and erosion risk classes.

Site	State	County	Lat (°N)	Long (°W)	Site type	Current vegetation	Slope	Drainage class	Erosion risk class
WI25	Wisconsin	Pierce	44.8	92.2	Agronomic	Hay	9-15%	Well Drained	Low
WI26	Wisconsin	Eau Claire	44.6	91.2	Agronomic	Corn	5-9%	Well Drained	Low
WI27	Wisconsin	Trempealeau	44.5	91.2	Agronomic	Alfalfa	9-15%	Well Drained	Medium
WI28	Wisconsin	Trempealeau	44.3	91.5	Agronomic	Agronomic	15-30%	Well Drained	Low
WI29	Wisconsin	Trempealeau	44.1	91.5	Agronomic	Soybean	9-15%	Well Drained	Low
WI30	Wisconsin	Vernon	43.7	91.0	Agronomic	Corn	9-15%	Well Drained	Low
WI31	Wisconsin	Vernon	43.6	90.9	Agronomic	Corn	9-15%	Well Drained	Medium
WI32	Wisconsin	Sauk	43.5	90.1	Agronomic	Soybean/alfalfa	9-15%	Well Drained	Medium
WI33	Wisconsin	Sauk	43.4	90.2	Agronomic	Corn	9-15%	Well Drained	Low
WI34	Wisconsin	Grant	43.0	90.6	Agronomic	CRP	9-15%	Well Drained	Low
WI35	Wisconsin	Grant	42.8	90.7	Agronomic	Corn	5-9%	Well Drained	Low
WI36	Wisconsin	Lafayette	42.8	90.4	Agronomic	Soybean	9-15%	Well Drained	Medium
WI37	Wisconsin	Lafayette	42.7	90.3	Agronomic	Corn	5-9%	Well Drained	Medium
WI38	Wisconsin	Iowa	43.0	89.8	Agronomic	Soybean	9-15%	Well Drained	Medium
WI39	Wisconsin	Green	42.9	89.7	Agronomic	Soybean	15-30%	Well Drained	Low
WI40	Wisconsin	Green	42.7	89.6	Agronomic	Agronomic	15-30%	Well Drained	Low
WI41	Wisconsin	Green	42.6	89.6	Agronomic	Corn	9-15%	Well Drained	Low
WI42	Wisconsin	Rock	42.7	88.9	Agronomic	Corn	2-5%	Well Drained	Low
WI43	Wisconsin	Rock	42.7	88.8	Agronomic	Corn	0-2%	Well Drained	Low
WI44	Wisconsin	Racine	42.7	88.2	Agronomic	Corn	0-2%	Well Drained	Low
WI45	Wisconsin	Racine	42.7	88.1	Agronomic	Corn	2-5%	Well Drained	Low
WI46	Wisconsin	Dodge	43.4	88.4	Agronomic	Corn	5-9%	Well Drained	Low
WI47	Wisconsin	Dodge	43.6	88.5	Agronomic	Corn	2-5%	Moderately Well Drained	Low
WI48	Wisconsin	Fond du Lac	43.7	88.8	Agronomic	Corn	2-5%	Moderately Well Drained	Low
WI49	Wisconsin	Green Lake	43.8	88.8	Agronomic	Soybean	2-5%	Moderately Well Drained	Low
WI50	Wisconsin	Manitowoc	43.8	87.9	Agronomic	Soybean	0-2%	Moderately Well Drained	Low
WI51	Wisconsin	Manitowoc	43.8	87.9	Agronomic	Corn	5-9%	Moderately Well Drained	Low
WI52	Wisconsin	Calumet	43.9	88.1	Agronomic	Corn	2-5%	Well Drained	Low
WI53	Wisconsin	Calumet	44.1	88.1	Agronomic	Corn	5-9%	Well Drained	Low
WI54	Wisconsin	Kewaunee	44.5	87.8	Agronomic	Corn	5-9%	Moderately Well Drained	Medium
WI55	Wisconsin	Kewaunee	44.6	87.7	Agronomic	CRP	2-5%	Moderately Well Drained	Low
WI56	Wisconsin	Outagamie	44.3	89.4	Agronomic	Corn	2-5%	Well Drained	Low
WI57	Wisconsin	Outagamie	44.5	88.4	Agronomic	Corn	5-9%	Moderately Well Drained	Medium
WI58	Wisconsin	Grant	42.8	90.8	Old Poplar Trial	Poplar	9-15%	Well Drained	Very Low
WI59	Wisconsin	Buffalo	44.5	91.7	Old Poplar Trial	Poplar	9-15%	Well Drained	Low

Appendix B: Soils Information

Site	Texture	pH	EC (mS cm^{-1})	g N kg^{-1}	g C kg^{-1}	g Ca kg^{-1}	mg Mg kg^{-1}	mg K kg^{-1}	mg Na kg^{-1}	CEC (cmol^{+} kg^{-1})	ECEC (cmol^{+} kg^{-1})
MN1	Loam	5.98±0.58	0.254±0.036	1.946±0.741	24.49±9.65	3.070±0.585	443.8±32.5	145.8±59.5	23.01±3.51	19.44±2.78	37.29±0.28
MN2	Sandy Loam	5.91±0.15	0.191±0.044	1.081±0.055	11.51±0.65	0.998±0.074	197.0±03.7	94.4±08.0	11.88±2.08	6.89±0.38	16.46±2.26
MN3	Sandy Loam	6.79±0.18	0.197±0.020	0.995±0.184	12.20±2.19	1.673±0.178	78.9±30.8	87.4±11.3	13.57±5.80	9.28±0.68	18.37±3.32
MN4	Sandy Loam	5.80±0.38	0.171±0.064	1.822±0.874	23.96±11.31	2.387±1.284	242.5±155.8	138.4±23.6	11.43±0.87	14.31±7.75	28.10±6.28
MN5	Silt Loam	5.23±0.10	0.098±0.007	1.176±0.234	15.82±2.83	0.983±0.043	121.2±05.1	69.0±15.5	11.14±0.64	6.13±0.23	23.92±2.17
MN6	Sandy Loam	5.44±0.13	0.146±0.019	1.532±0.244	19.42±3.69	1.672±0.224	260.9±30.7	83.5±15.3	16.78±0.95	10.78±1.40	24.46±3.75
MN7	Loam	5.58±0.15	0.178±0.026	1.903±0.432	22.76±4.89	1.790±0.140	283.5±25.3	151.4±74.9	27.4±1.10	11.77±1.07	29.19±0.96
MN8	Loamy Sand	5.43±0.05	0.068±0.006	0.582±0.064	07.14±0.63	0.748±0.109	30.4±13.9	73.5±04.0	11.35±0.31	4.22±0.67	18.19±1.48
MN9	Loamy Sand	5.31±0.07	0.098±0.007	1.170±0.210	14.29±2.06	0.560±0.107	72.5±18.2	56.3±04.8	11.34±1.32	3.59±0.68	20.49±1.28
MN10	Sandy Loam	5.05±0.04	0.054±0.005	0.821±0.104	10.01±1.26	0.869±0.105	78.1±12.9	63.1±03.0	7.73±0.31	5.18±0.63	20.20±2.00
MN11	Sand	6.22±0.23	0.187±0.040	1.207±0.302	18.96±5.25	1.197±0.183	170.2±21.3	72.9±13.3	6.88±0.37	7.59±1.11	29.67±3.34
MN12	Sandy Loam	5.55±0.06	0.092±0.004	1.187±0.047	13.01±1.19	1.554±0.089	200.6±20.5	68.9±02.8	9.31±0.73	9.62±0.60	19.75±5.80
MN13	Sandy Loam	7.43±0.07	0.380±0.013	2.488±0.471	37.93±2.55	3.842±0.309	612.3±43.3	128.3±08.7	6.69±0.82	24.57±1.89	28.14±1.76
MN14	Sandy Loam	7.49±0.02	0.399±0.023	2.625±0.193	44.62±5.08	4.172±0.130	659.7±91.6	70.1±05.5	11.28±2.66	26.48±1.26	31.45±2.12
MN15	Loamy Sand	7.48±0.05	0.357±0.048	1.958±0.352	25.93±4.95	3.433±0.399	633.5±74.2	69.0±08.1	16.03±4.06	22.59±2.54	30.98±3.50
MN16	Loam	7.73±0.01	0.511±0.040	1.549±0.139	25.09±1.61	2.966±0.159	871.6±189.1	106.6±06.9	59.94±18.97	22.51±2.38	29.85±2.29
MN17	Loam	7.54±0.04	0.413±0.011	2.766±0.410	38.69±6.46	3.892±0.047	791.7±152.0	138.3±10.8	24.56±3.86	26.40±1.07	37.83±1.27
MN18	Sandy Loam	7.56±0.02	0.293±0.046	2.030±0.665	29.33±7.08	2.831±0.318	279.9±118.1	52.3±02.7	19.14±12.92	16.65±2.59	28.43±5.72
MN19	Sandy Loam	7.60±0.01	0.279±0.016	2.182±0.231	25.42±3.40	2.800±0.163	311.7±40.3	56.2±02.2	10.67±1.46	16.73±1.15	26.74±3.37
MN20	Clay Loam	7.28±0.11	0.393±0.013	2.298±0.463	29.05±3.99	4.723±0.625	780.1±76.9	143.0±04.2	15.24±1.12	30.42±3.58	45.74±3.44
MN21	Sandy Loam	7.24±0.04	0.320±0.018	1.272±0.072	13.16±2.33	2.216±0.258	426.6±77.2	111.0±10.9	12.98±4.10	14.91±0.78	26.77±1.74
MN22	Loam	7.66±0.06	1.984±0.779	3.908±0.142	55.56±1.10	5.396±0.235	1351.8±331.5	138.1±06.7	238.72±111.27	39.44±3.65	42.52±2.83
MN23	Loam	7.66±0.02	0.544±0.081	1.930±0.234	42.00±1.91	3.305±0.255	889.4±66.5	113.9±10.3	44.22±6.50	24.30±1.77	29.54±1.22
MN24	Sandy Loam	7.66±0.01	0.539±0.174	1.580±0.155	23.22±0.23	2.498±0.304	429.2±22.8	94.1±05.9	52.65±31.89	16.47±1.83	19.33±1.91
MN25	Clay Loam	7.72±0.10	0.825±0.172	2.477±0.177	37.58±2.74	4.072±0.579	2012.1±190.9	243.2±14.1	147.42±57.41	38.14±1.65	47.56±2.93
MN26	Sandy Loam	7.73±0.05	0.373±0.026	1.602±0.120	26.44±1.04	2.691±0.093	800.1±105.9	78.8±03.0	25.25±9.14	20.32±0.60	27.02±1.08
MN27	Silty Clay Loam	7.65±0.02	0.538±0.036	2.693±0.057	48.56±1.24	4.736±0.079	1346.0±69.9	305.9±17.1	59.84±21.21	35.75±1.00	42.05±0.56
MN28	Loam	7.86±0.02	0.638±0.104	2.296±0.164	50.77±1.26	2.189±0.109	989.9±54.9	125.9±21.1	100.68±21.85	19.83±1.09	31.51±1.17
MN29	Sandy Clay Loam	7.53±0.05	0.477±0.007	2.445±0.192	28.94±2.35	3.814±0.415	1027.7±65.0	250.0±36.2	86.80±21.05	28.51±2.51	41.27±3.82
MN30	Loam	7.39±0.06	1.675±0.619	2.295±0.093	24.91±1.17	4.224±0.338	1368.1±247.6	230.2±28.3	259.49±106.43	34.05±2.96	41.81±1.23
MN31	Loam	7.40±0.04	0.516±0.043	2.385±0.233	29.50±2.98	4.434±0.207	897.2±154.5	252.2±29.3	24.09±9.66	30.26±0.59	48.23±2.92
MN32	Clay Loam	7.69±0.04	0.867±0.318	2.770±0.206	42.94±0.94	3.97±0.292	965.9±82.8	286.1±07.2	39.05±7.52	28.66±2.17	40.53±0.70
MN33	Sandy Loam	5.89±0.22	0.171±0.070	1.610±0.239	15.99±3.38	1.324±0.144	165.3±21.4	84.3±11.1	11.45±1.14	8.23±0.87	16.60±2.44
MN34	Sandy Loam	6.14±0.21	0.158±0.027	1.977±0.319	21.64±3.66	2.784±0.600	218.4±51.9	57.2±01.1	14.97±0.64	15.90±3.42	22.29±3.07
MN35	Sandy Loam	5.34±0.05	0.119±0.013	1.395±0.062	11.41±1.11	0.726±0.082	80.1±03.3	76.1±05.7	8.90±0.73	4.52±0.39	11.92±0.47
MN36	Sandy Loam	6.47±0.11	0.252±0.028	2.067±0.360	22.35±5.15	3.328±0.085	552.9±24.5	141.0±56.2	20.04±4.47	21.60±0.60	27.23±1.66
MN37	Loam	5.85±0.09	0.121±0.017	2.099±0.069	22.56±0.92	2.220±0.221	154.9±06.3	130.0±38.6	9.30±1.01	12.72±0.98	16.02±2.04
MN38	Sandy Clay Loam	7.62±0.02	0.450±0.005	3.371±0.083	52.50±0.51	4.364±0.120	970.5±45.8	161.3±01.5	36.17±16.75	30.33±0.59	36.10±1.06

Appendix B: Soils Information

Site	Texture	pH	EC (mS cm^{-1})	g N kg^{-1}	g C kg^{-1}	g Ca kg^{-1}	mg Mg kg^{-1}	mg K kg^{-1}	mg Na kg^{-1}	CEC ($cmol^{+}$ kg^{-1})	ECEC ($cmol^{+}$ kg^{-1})
MN39	Sandy Loam	6.57±0.33	0.160±0.025	1.225±0.094	14.69±2.33	1.522±0.399	258.1±87.1	181.2±20.7	7.47±1.09	10.22±2.72	15.70±4.29
MN40	Clay Loam	6.40±0.14	0.249±0.048	1.551±0.076	13.96±1.09	2.679±0.230	564.2±54.1	193.6±08.6	14.65±1.29	18.57±1.53	24.79±1.75
MN41	Sandy Loam	5.96±0.19	0.075±0.010	1.234±0.101	11.31±1.45	0.982±0.022	105.7±13.1	46.2±05.5	9.21±0.08	5.93±0.05	11.08±1.83
MN42	Sandy Loam	6.59±0.15	0.265±0.038	1.907±0.095	17.70±1.08	2.617±0.061	407.9±10.8	165.7±13.4	21.78±1.74	16.93±0.37	23.80±0.73
MN43	Sandy Loam	6.44±0.19	0.437±0.136	3.429±0.225	40.72±2.62	3.455±0.331	557.9±40.5	151.1±22.9	16.33±1.38	22.29±2.01	30.45±1.80
MN44	Sandy Loam	5.41±0.09	0.126±0.010	2.068±0.245	21.59±2.31	1.887±0.129	322.9±39.1	132.4±19.9	7.35±0.67	12.44±0.99	24.13±1.14
MN45	Clay Loam	5.96±0.03	0.138±0.012	1.729±0.031	16.86±0.62	2.982±0.050	485.3±39.3	159.4±08.9	12.87±0.48	19.34±0.59	34.74±2.16
MN46	Loam	7.33±0.09	0.287±0.025	1.000±0.119	25.78±0.88	3.022±0.511	310.9±25.4	127.3±17.6	24.15±3.99	18.07±2.77	27.80±3.14
MN47	Silt Loam	7.36±0.02	0.294±0.017	1.908±0.122	23.70±1.32	4.381±0.269	341.4±08.8	118.0±13.6	19.45±3.14	25.06±1.32	29.91±1.38
MN48	Loam	6.32±0.40	0.317±0.065	2.972±0.147	34.32±2.26	4.562±0.242	667.2±17.6	227.5±30.6	19.26±1.96	28.92±1.16	36.39±0.79
MN49	Sandy Loam	7.12±0.19	0.513±0.013	2.328±0.268	30.84±2.02	5.241±0.296	785.8±61.3	262.1±16.5	23.65±4.17	33.39±1.86	41.30±1.31
MN50	Clay Loam	7.32±0.02	0.384±0.004	2.472±0.278	28.86±3.78	5.532±0.266	851±88.4	185.6±02.3	20.02±2.04	35.17±1.88	41.11±1.68
MN51	Clay Loam	7.51±0.02	0.376±0.012	1.947±0.149	37.88±3.63	5.064±0.190	572.8±60.6	170.7±06.7	26.26±1.20	30.54±1.45	35.96±1.46
MN52	Loam	7.26±0.01	0.407±0.010	2.920±0.029	38.19±1.00	5.042±0.273	790.3±86.4	318.9±23.3	14.31±2.07	32.54±0.92	40.46±0.07
MN53	Loam	7.14±0.14	0.360±0.010	2.309±0.106	26.25±1.30	4.693±0.235	599.6±124.0	206.8±08.2	11.05±0.36	28.93±0.68	34.28±0.81
MN54	Silty Clay Loam	7.68±0.05	0.581±0.066	2.227±0.137	33.25±3.49	4.078±0.284	1238.5±91.6	338.8±73.3	58.49±6.88	31.66±0.58	38.88±0.79
MN55	Sandy Loam	6.89±0.15	0.299±0.082	2.215±0.198	21.45±1.97	3.405±0.028	613.0±05.2	233.3±107.9	22.16±1.51	22.73±0.40	26.60±1.11
MN56	Clay Loam	7.50±0.04	0.338±0.018	1.595±0.169	21.58±2.05	4.682±0.373	497.6±57.8	186.1±16.4	21.08±2.41	28.02±2.04	32.48±2.33
MN57	Clay Loam	7.48±0.01	0.445±0.013	2.864±0.114	35.87±1.28	5.540±0.175	733.2±40.3	212.8±13.5	19.28±1.64	34.31±1.19	41.94±2.02
MN58	Clay Loam	5.93±0.03	0.230±0.019	2.579±0.142	31.00±2.35	4.592±0.118	1146.3±59.4	223.0±21.4	19.81±1.15	33.01±1.05	39.38±0.20
MN59	Loam	7.33±0.06	0.681±0.054	6.290±0.156	84.39±2.05	6.262±0.377	956.4±79.7	292.3±45.3	32.18±0.89	40.01±2.45	56.11±2.11
MN60	Silty Clay Loam	7.45±0.02	0.350±0.006	2.063±0.082	24.18±0.71	4.814±0.174	743.1±39.5	159.9±06.2	13.48±0.28	30.61±0.92	35.82±1.82
MN61	Silty Clay Loam	7.14±0.04	0.343±0.035	2.682±0.042	31.22±0.48	5.127±0.041	1128.8±67.3	174.2±03.7	14.35±0.36	35.38±0.75	40.18±0.23
MN62	Silty Clay Loam	7.27±0.15	1.030±0.330	3.908±0.181	45.74±2.49	5.970±0.160	1007.9±40.7	192.7±03.2	50.95±12.31	38.80±1.01	46.58±1.36
MN63	Silt Loam	6.81±0.12	0.272±0.020	2.502±0.157	27.40±1.94	4.194±0.225	877.1±29.5	177.5±18.7	14.33±0.12	28.66±1.20	33.59±0.72
MN64	Silty Clay Loam	6.93±0.02	0.305±0.022	2.689±0.058	28.03±1.30	4.320±0.111	1034.3±42.6	201.9±12.4	15.68±0.64	30.65±0.93	34.40±0.58
MN65	Loam	7.13±0.15	0.452±0.062	3.319±0.354	45.16±5.66	6.233±0.790	740.7±83.4	185.2±43.4	19.01±3.24	37.76±4.63	43.49±4.91
MN66	Loam	7.32±0.02	0.337±0.012	1.761±0.087	23.27±0.68	4.702±0.190	487.3±14.3	159.7±01.4	16.69±0.39	27.95±1.05	32.22±1.78
MN67	Clay Loam	5.32±0.13	0.136±0.004	2.171±0.075	23.02±0.58	3.514±0.011	580.6±17.7	183.4±02.2	15.44±0.48	22.85±0.13	28.75±0.74
MN68	Loam	6.78±0.14	0.280±0.025	2.078±0.283	20.02±2.94	3.445±0.058	758.6±49.1	239.9±43.8	33.78±4.56	24.20±0.76	30.04±0.70
MN69	Loam	6.72±0.28	0.180±0.016	1.939±0.033	21.06±0.65	2.525±0.094	539.0±43.4	142.6±26.7	10.95±0.98	17.45±0.75	23.33±0.61
MN70	Clay Loam	7.11±0.07	0.292±0.031	2.040±0.050	22.26±1.03	2.589±0.084	640.7±28.2	251.0±44.7	15.53±4.80	18.90±0.34	26.70±0.78
MN71	Clay Loam	7.00±0.04	0.375±0.010	3.340±0.309	41.44±4.42	4.494±0.641	976.3±91.9	224.9±07.8	14.92±0.85	31.10±3.93	42.16±6.87
MN72	Silt Loam	6.95±0.01	0.255±0.015	1.831±0.034	21.75±1.24	2.957±0.109	703.8±19.7	112.7±05.3	35.66±13.98	20.99±0.47	22.46±1.07
MN73	Silt Loam	7.09±0.18	0.414±0.045	4.273±0.294	53.18±4.19	5.724±0.871	482.4±30.9	222.6±28.5	18.47±3.86	33.18±4.11	41.99±7.17
MN74	Silt Loam	6.79±0.04	0.319±0.032	1.599±0.065	15.15±1.01	2.212±0.084	494.1±27.7	178.4±10.8	11.2.00±0.83	15.61±0.61	18.44±0.66
MN75	Silty Clay Loam	6.71±0.07	0.186±0.014	1.535±0.066	17.03±0.27	3.155±0.071	548.1±15.7	120.8±03.6	9.00±0.18	20.60±0.49	21.44±0.45

Appendix B: Soils Information

Site	Texture	pH	EC (mS cm^{-1})	g N kg^{-1}	g C kg^{-1}	g Ca kg^{-1}	mg Mg kg^{-1}	mg K kg^{-1}	mg Na kg^{-1}	CEC ($cmol^{+}$ kg^{-1})	ECEC ($cmol^{+}$ kg^{-1})
MN76	Missing	5.64±0.06	0.092±0.010	0.815±0.098	09.10±1.37	0.656±0.052	66.9±14.6	126.3±07.3	20.37±3.65	4.24±0.37	12.85±1.74
MN77	Missing	7.66±0.03	0.391±0.013	3.213±0.275	58.33±3.72	3.255±0.064	758.4±165.9	89.6±05.5	13.12±3.21	22.77±1.58	29.78±1.75
MN78	Missing	6.35±0.38	0.138±0.016	1.052±0.277	12.83±4.48	1.035±0.131	107.6±07.0	103.9±03.6	16.13±0.51	6.39±0.71	16.36±1.75
MN79	Missing	6.58±0.23	0.209±0.052	1.329±0.229	16.30±3.59	1.625±0.306	194.1±09.5	98.6±13.9	17.18±2.94	10.03±1.64	22.41±1.69
MN80	Missing	6.99±0.31	0.266±0.059	1.624±0.385	23.17±5.10	3.112±0.320	380.9±39.7	172.5±35.2	29.04±15.68	19.23±1.80	30.97±3.92
MN81	Missing	6.79±0.30	0.218±0.056	1.222±0.088	13.42±1.44	2.784±0.239	339.9±09.8	226.8±04.8	14.21±0.52	17.33±1.27	29.93±1.68
MN82	Missing	7.09±0.22	0.364±0.013	2.163±0.215	28.64±2.26	4.186±0.270	587.6±61.6	278.3±10.5	14.86±1.79	26.50±1.77	36.71±1.73
MN83	Missing	7.29±0.11	0.356±0.019	1.807±0.177	24.46±1.15	3.580±0.214	431.0±56.3	207.7±16.2	10.44±0.66	21.99±1.57	31.42±0.15
MN84	Missing	7.01±0.10	0.394±0.020	3.341±0.349	40.45±4.05	5.194±0.261	662.0±47.3	197.0±10.3	15.16±0.24	31.94±1.70	38.27±2.24
WI1	Silt Loam	6.16±0.08	0.283±0.034	3.135±0.523	40.22±9.14	3.617±0.364	625.3±64.8	450.7±37.6	6.08±0.65	24.37±2.37	31.29±5.49
WI2	Silt Loam	6.63±0.04	0.148±0.005	1.301±0.052	15.28±0.52	2.503±0.029	727.6±25.1	107.5±06.1	27.54±4.11	18.87±0.17	24.73±0.72
WI3	Silt Loam	6.74±0.03	0.218±0.010	1.803±0.080	20.59±0.86	2.927±0.156	781.1±58.2	202.9±35.1	23.58±3.55	21.65±1.13	30.03±1.55
WI4	Loamy Sand	5.03±0.05	0.088±0.009	1.049±0.092	16.40±1.82	0.720±0.074	92.1±40.1	143.0±24.0	3.10±0.97	4.73±0.54	17.46±0.95
WI5	Sandy Loam	5.30±0.14	0.067±0.004	0.925±0.164	12.89±2.73	0.651±0.095	154.5±24.2	60.4±07.1	5.70±0.52	4.70±0.67	20.73±0.61
WI6	Silt Loam	4.55±0.07	0.094±0.005	1.118±0.144	14.19±2.46	0.624±0.038	78.5±10.9	38.9±02.9	12.51±1.30	3.91±0.13	21.09±0.56
WI7	Sandy Loam	5.10±0.12	0.103±0.006	1.456±0.127	19.61±1.37	0.848±0.083	113.6±28.0	72.0±05.1	4.45±0.57	5.37±0.61	22.60±1.04
WI8	Silt Loam	6.48±0.04	0.226±0.011	1.774±0.113	20.18±1.38	2.025±0.051	414.9±15.8	94.5±11.6	51.83±10.66	13.99±0.34	28.45±0.97
WI9	Silt	6.34±0.05	0.168±0.021	1.723±0.364	16.70±4.29	1.493±0.100	380.6±16.4	92.7±26.3	32.96±5.51	10.96±0.65	23.97±0.17
WI10	Silt Loam	5.49±0.21	0.130±0.004	1.537±0.167	15.59±1.54	1.380±0.100	338.7±59.0	72.1±06.7	25.72±0.44	9.97±0.97	21.53±1.49
WI11	Silt	6.37±0.03	0.243±0.010	2.158±0.148	22.59±1.91	2.111±0.082	511.7±33.0	173.8±36.5	90.55±13.69	15.59±0.72	19.84±0.74
WI12	Silt	5.51±0.28	0.115±0.016	1.472±0.161	16.02±2.29	1.483±0.190	278.3±24.1	41.9±03.2	18.76±2.32	9.88±1.07	15.99±1.17
WI13	Silt Loam	4.68±0.04	0.116±0.016	2.254±0.330	23.92±3.89	1.077±0.073	222.1±18.3	95.4±20.1	14.90±1.26	7.51±0.56	20.14±1.08
WI14	Sandy Loam	4.97±0.16	0.073±0.002	0.956±0.199	10.52±2.57	0.591±0.055	75.0±12.4	41.1±08.4	14.28±2.28	3.74±0.38	18.03±1.69
WI15	Silt Loam	6.15±0.18	0.106±0.022	1.908±0.233	22.15±2.67	1.474±0.176	347.1±46.4	74.2±10.4	5.41±0.31	10.42±1.24	25.89±0.32
WI16	Sand	6.04±0.16	0.166±0.027	2.177±1.013	34.15±17.77	1.189±0.281	75.5±31.7	55.6±08.1	51.16±37.28	6.92±1.81	27.45±2.92
WI17	Sandy Loam	6.34±0.14	0.141±0.018	1.202±0.091	13.98±1.90	1.580±0.199	258.9±38.0	150.6±14.8	9.62±1.35	10.44±1.31	24.72±1.47
WI18	Loam	4.73±0.09	0.241±0.034	1.427±0.089	14.51±0.75	0.536±0.025	94.7±06.4	206.5±28.2	7.16±0.89	4.02±0.23	22.21±0.18
WI19	Silt Loam	5.21±0.12	0.136±0.009	1.977±0.153	35.02±4.30	1.339±0.115	254.1±35.0	49.7±08.3	10.27±1.81	8.95±0.86	16.26±2.55
WI20	Silt Loam	6.13±0.03	0.152±0.010	1.516±0.072	17.04±1.38	1.686±0.037	450.9±13.8	177.0±25.2	9.90±0.98	12.62±0.36	27.31±1.33
WI21	Sandy Loam	6.43±0.11	0.152±0.009	1.217±0.085	13.77±1.05	1.143±0.04	275.6±33.1	177.2±20.8	4.64±0.23	8.44±0.52	12.73±0.79
WI22	Silt Loam	6.52±0.04	0.161±0.009	1.687±0.142	18.14±1.74	1.794±0.082	514.7±13.5	94.5±20.1	12.55±2.05	13.48±0.55	25.38±1.36
WI23	Silt Loam	5.74±0.04	0.146±0.007	1.418±0.063	14.16±1.35	1.247±0.049	312.9±14.0	212.4±02.6	6.96±0.17	9.37±0.29	23.58±1.47
WI24	Silt Loam	6.30±0.08	0.169±0.008	1.518±0.197	15.06±1.86	2.037±0.071	503.2±06.8	103.7±09.0	11.55±1.49	14.62±0.42	26.25±0.31
WI25	Silt Loam	5.92±0.09	0.134±0.010	1.931±0.095	18.72±1.30	2.400±0.094	363.8±27.2	69.8±06.7	18.36±3.53	15.23±0.57	27.41±0.22
WI26	Silt Loam	5.97±0.14	0.180±0.031	1.678±0.117	18.76±1.56	2.513±0.140	436.8±19.4	59.4±07.3	13.04±1.37	16.34±0.69	24.39±1.24
WI27	Silt Loam	6.20±0.11	0.128±0.006	1.281±0.166	12.50±1.97	1.586±0.251	312.6±12.1	65.7±04.3	10.75±1.25	10.70±1.36	18.04±2.47
WI28	Silt Loam	6.75±0.07	0.175±0.005	1.390±0.065	14.62±1.21	2.445±0.075	558.9±23.6	99.2±06.8	32.96±5.00	17.20±0.58	20.92±0.10

Appendix B: Soils Information

Site	Texture	pH	EC (mS cm^{-1})	g N kg^{-1}	g C kg^{-1}	g Ca kg^{-1}	mg Mg kg^{-1}	mg K kg^{-1}	mg Na kg^{-1}	CEC (cmol^{+} kg^{-1})	ECEC (cmol^{+} kg^{-1})
WI29	Silt Loam	6.12±0.18	0.196±0.033	2.189±0.287	27.58±4.54	3.808±0.247	802.7±54.9	152.4±31.5	17.11±3.55	26.07±1.73	28.00±1.63
WI30	Silt Loam	6.62±0.03	0.188±0.015	1.185±0.118	10.43±1.42	1.980±0.031	593.6±26.1	111.0±06.0	10.90±1.08	15.10±0.34	19.85±0.12
WI31	Silt Loam	6.26±0.19	0.138±0.018	1.811±0.180	22.06±2.52	2.821±0.222	706.1±33.5	131.1±12.5	8.80±0.93	20.26±1.38	26.60±1.83
WI32	Silt Loam	6.88±0.02	0.206±0.003	1.714±0.057	18.97±0.59	1.891±0.042	495.5±18.2	194.1±26.5	34.86±5.03	14.16±0.32	23.03±1.58
WI33	Silt Loam	6.82±0.04	0.184±0.003	1.185±0.099	10.22±1.12	2.046±0.029	653.1±12.9	86.7±03.9	22.84±0.65	15.91±0.15	21.58±1.47
WI34	Silt Loam	6.30±0.02	0.163±0.016	1.950±0.152	21.23±1.64	2.617±0.084	689.1±22.6	171.7±14.5	10.99±1.35	19.22±0.59	27.47±1.44
WI35	Silt Loam	6.79±0.07	0.207±0.005	1.559±0.079	17.33±0.96	2.929±0.021	741.4±18.6	155.3±06.3	12.85±0.35	21.17±0.16	28.97±0.91
WI36	Silty Clay Loam	6.84±0.01	0.235±0.010	1.661±0.141	18.74±1.73	3.169±0.040	796.0±15.6	249.4±32.7	12.28±1.70	23.06±0.29	26.76±0.34
WI37	Silty Clay Loam	6.70±0.03	0.189±0.030	1.508±0.109	17.26±2.17	2.713±0.147	765.5±48.8	219.0±57.8	15.64±2.68	20.46±0.97	24.18±1.24
WI38	Silt Loam	6.59±0.13	0.228±0.007	2.271±0.058	25.68±0.86	3.297±0.145	947.9±19.5	135.6±08.7	8.32±0.29	24.64±0.86	30.63±0.10
WI39	Silt Loam	6.81±0.04	0.226±0.010	1.322±0.240	14.54±3.52	2.652±0.236	911.1±157.5	106.5±14.6	13.99±1.47	21.06±2.51	24.94±3.03
WI40	Silt Loam	6.37±0.34	0.189±0.013	1.675±0.132	17.24±1.94	2.654±0.136	671.6±150.8	127.3±09.6	8.94±1.08	19.14±1.90	27.05±2.27
WI41	Silt Loam	6.97±0.10	0.295±0.038	2.134±0.038	28.28±3.24	2.778±0.053	883.3±34.6	129.9±13.3	22.45±4.41	21.56±0.55	29.35±0.97
WI42	Silt Loam	6.41±0.05	0.189±0.022	1.650±0.172	19.58±2.14	2.955±0.081	908.9±43.3	110.5±07.2	11.89±0.57	22.56±0.46	29.39±1.66
WI43	Silt Loam	5.60±0.23	0.194±0.038	1.654±0.115	19.22±1.16	2.241±0.230	517.6±47.1	202.8±41.2	11.52±1.68	16.01±1.36	27.72±3.39
WI44	Silt Loam	7.04±0.03	0.306±0.014	2.067±0.241	24.60±2.43	3.024±0.340	711.6±87.1	96.4±04.1	31.68±5.86	21.33±2.42	34.44±5.20
WI45	Silty Clay	6.82±0.19	0.220±0.008	1.741±0.175	19.82±2.39	2.760±0.103	799.4±37.3	195.8±20.8	9.07±0.32	20.89±0.58	35.33±2.37
WI46	Silt Loam	6.66±0.12	0.228±0.004	1.907±0.042	19.84±0.44	2.413±0.047	697.6±44.7	79.7±06.7	20.21±1.03	18.07±0.61	36.31±0.79
WI47	Silt Loam	7.25±0.04	0.343±0.035	1.434±0.171	18.63±1.61	2.621±0.074	888.1±24.6	105.4±25.6	46.43±6.79	20.86±0.56	38.07±0.04
WI48	Silt Loam	6.85±0.07	0.248±0.020	2.447±0.107	31.73±1.19	3.531±0.270	1127.4±113.4	198.4±11.6	17.14±5.01	27.48±2.29	45.07±1.74
WI49	Silt Loam	7.05±0.03	0.273±0.016	1.774±0.097	29.72±1.69	2.775±0.128	799.0±21.6	142.5±04.5	21.48±4.32	20.88±0.81	38.27±0.13
WI50	Clay Loam	7.20±0.08	0.264±0.039	1.185±0.060	19.90±4.82	2.101±0.169	629.7±69.3	130.5±38.0	20.05±2.27	16.09±1.52	35.71±0.96
WI51	Clay Loam	7.31±0.05	0.395±0.083	1.219±0.169	17.48±1.30	2.029±0.127	695.8±45.6	140.0±08.7	247.58±64.63	17.29±0.16	29.03±1.21
WI52	Silt Loam	7.34±0.05	0.344±0.011	1.656±0.104	20.83±2.54	2.247±0.091	614.0±38.0	102.4±14.1	50.48±0.76	16.75±0.8	28.08±2.12
WI53	Silty Clay Loam	7.20±0.06	0.298±0.022	1.342±0.189	22.22±1.19	3.295±0.325	1007.5±56.1	170.8±13.8	19.21±4.01	25.25±2.02	33.20±2.48
WI54	Sandy Loam	7.05±0.11	0.304±0.029	1.651±0.529	31.87±8.24	2.075±0.212	323.6±47.5	361.6±108.2	10.78±1.58	13.99±1.57	26.79±1.13
WI55	Clay Loam	7.25±0.04	0.279±0.040	1.334±0.256	17.22±2.88	2.568±0.094	625.8±18.5	132.0±07.6	20.82±2.35	18.39±0.41	36.30±0.75
WI56	Loam	7.35±0.07	0.431±0.082	1.567±0.204	18.28±2.66	2.410±0.255	477.8±37.9	197.2±43.8	91.19±35.57	16.86±1.73	35.45±1.07
WI57	Sandy Loam	7.35±0.05	0.258±0.002	0.684±0.106	10.94±0.08	1.860±0.153	296.3±31.4	138.4±55.1	27.58±2.36	12.19±0.89	29.34±2.40
WI58	Silt Loam	6.48±0.09	0.138±0.006	1.140±0.087	13.48±1.41	1.629±0.055	489.4±34.5	100.3±15.8	11.61±0.51	12.46±0.56	34.32±2.50
WI59	Silt Loam	5.47±0.16	0.091±0.006	1.078±0.094	14.49±1.54	1.343±0.066	227.7±22.1	105.1±07.6	3.69±0.65	8.86±0.53	29.87±3.36

Key: EC=electrical conductivity; N=nitrogen; C=carbon; Ca=calcium; Mg=magnesium; K=potassium; Na=sodium; CEC=cation exchange capacity; ECEC=effective cation exchange capacity.

Appendix C: Supplemental Information from 3-PG Modeling

Fertility Rating Equation

The fertility rating equation in 3-PG is of the form:

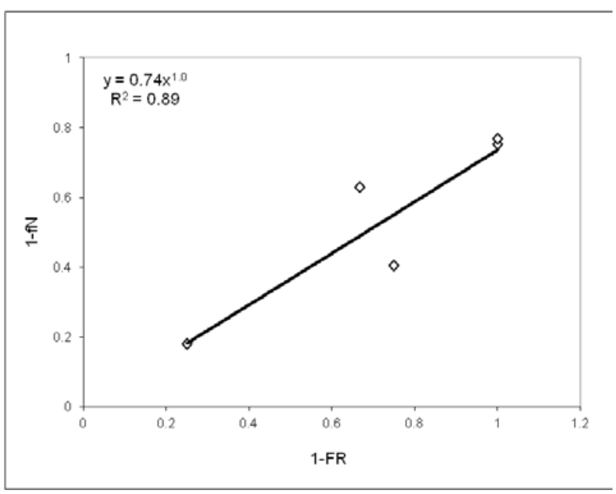
$$f_N = 1 - (1 - f_{N0}) \times (1 - FR)^{nfN} \quad (2)$$

which can be re-arranged as:

$$(1 - f_N) = (1 - f_{N0}) \times (1 - FR)^{nfN} \quad (3)$$

where f_N is the proportion of actual versus potential growth at a given FR, f_{N0} is the proportion of actual versus potential growth when FR = 0, FR is a measure of fertility, and n_{fN} is a species-specific coefficient.
Possible metrics for fertility include but are not limited to applied fertilizer rates, soil nutrient levels, and/or plant nutrient levels. Here, plant nutrient levels are considered as they reflect realized site fertility, whereas the other metrics reflect potential site fertility and are subject to confounding factors such as fertilizer type and placement, as well as soil conditions which may interfere with nutrient uptake.

Data from Table 2 (stem volume) and Figure 2a (leaf N concentration) in a fertility study of four *Populus trichocarpa* × *P. deltoides* clones (van den Driessche, 1999) were converted to relative scales such that for stem volume, 0 = no stem volume, and 1 = maximum reported stem volume; and for leaf N concentration, 0 = minimum reported leaf N, and 1 = maximum reported leaf N. Relative stem volume and relative leaf N were then used as measures of f_N and FR, respectively, to solve for f_{N0} and n_{fN} in the re-arranged equation above, using linear regression (see below). The resulting values of the parameters are estimated as: $(1- f_{N0}) = 0.74$, thus $f_{N0} = 0.26$; $n_{fN} = 1$.



Relationship between relative stem volume (f_N) and relative leaf N concentration (FR) derived from a previous study of four *Populus trichocarpa* × *Populus deltoides* clones (van den Driessche, 1999).

Stem Height Relationship

The height equation in 3-PG is of the form:

$$H = a_H \times B^{nHB} \times N^{nHN} \quad (4)$$

or when log-transformed

$$\ln H = \ln a_H + n_{HB}(\ln B) + n_{HN}(\ln N) \quad (5)$$

where H is mean tree height, B is mean tree diameter at breast height (DBH), N is trees per unit area, and the remaining variables (a_H, n_{HB}, and n_{HN}) are species-specific coefficients.

Data from Table 1 (mean heights in meters, mean DBH in centimeters, and trees per hectare derived from tree spacing) of a previous study with *Populus trichocarpa* × *P. deltoides* and *P. trichocarpa* × *P. nigra* clones (DeBell et al., 1996) were log-transformed and evaluated in SAS with linear regression (PROC REG), solving for log-transformed height. The resulting model (R^2 = 0.98) estimates the values of the coefficients as: n_{HB} = 1.335; n_{HN} = 0.354; a_H = 0.036.

Stem Volume Relationship

The volume equation in 3-PG is of the form:

$$V_S = a_V \times B^{nVB} \times N^{nVN} \quad (6)$$

or when log-transformed

$$\ln V_S = \ln a_V + n_{VB}(\ln B) + n_{VN}(\ln N) \quad (7)$$

where V_S is mean tree stem volume, B is mean tree diameter at breast height (DBH), N is trees per unit area, and the remaining variables (a_V, n_{VB}, and n_{VN}) are species-specific coefficients.

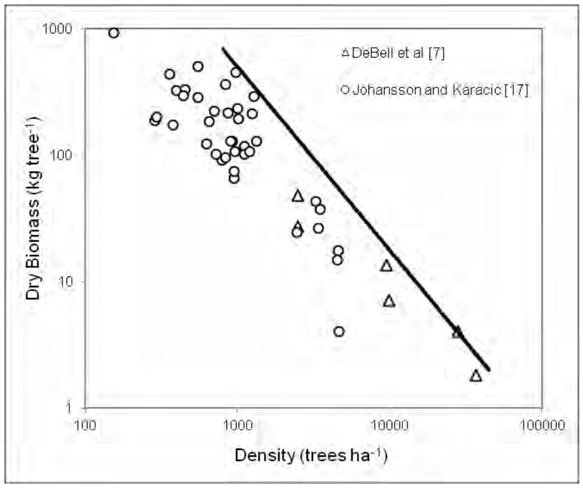
From Table 1 (trees per hectare) and Table 2 (DBH in centimeters, and volume estimated from mean annual mass increment × age × basic density) of a study on an array of hybrid poplars (Johansson and Karacic, 2011), data were log transformed and evaluated in SAS with linear regression (PROC REG) solving for log-transformed volume. Because stocking was reported at the stand level, and the data used to estimate stem volume was derived from individual trees within the stands, only individual trees having diameters within 20% of the mean stand diameter were used, under the assumption that individual trees similar to the stand mean were growing at (or near) average density conditions. The resulting model (R^2 = 0.72) estimates the values of the coefficients as: n_{VB} = 1.96; n_{VN} = -0.30; a_V = 0.0072.

Self-Thinning Relationship

The self-thinning relationship in 3-PG is described by the equation:

$$wSx = wSx1000 \left(\frac{1000}{N}\right)^{nN} \quad (8)$$

where w_{Sx} is maximum tree biomass, N is stand density, and the remaining variables are species-specific coefficients representing maximum tree biomass at 1,000 tree per hectare (w_{Sx1000}) and the slope of the self-thinning line (n_N). Stand density and mean stem biomass values were derived from Table 1 of DeBell et al. (1996) and Table 1 of Johansson and Karacic (2011). The former reported these two variables directly; the latter reported stand density and mean stem diameter, which was converted to mean stem biomass using Equation 2 from that study. The data were then graphed, and the location of the self-thinning line was estimated by iteratively manipulating the slope and intercept (at 1,000 trees per hectare) to visually match the upper boundary of tree biomass across stand densities (see below). The resulting values of the coefficients are estimated as: w_{Sx1000} = 500; n_N = -1.45.



Estimated self-thinning line for hybrid poplars based on data from two previously-published studies (DeBell et al., 1996; Johansson and Karacic, 2011).

Foliage:Stem Partitioning

The ratio of foliage:stem biomass in 3-PG is described by the equation:

$$p_{FS} = a_p \times B^{nP} \tag{9}$$

where p_{FS} is the foliage:stem ratio, B is mean stem diameter at breast height (DBH), and the remaining variables (a_p and n_P) are species-specific coefficients.

In 3-PG, these coefficients are estimated from foliage:stem ratios measured at 2 cm DBH (p_{FS2}) and 20 cm DBH (p_{FS20}). Equations from Table 3 in Fortier et al. (2010) were used to estimate stem (main stem + branch) and foliage biomass at DBH = 20 for the *P. deltoides* × *P. nigra* clone '3570'; these biomass values were then used to calculate the foliage:stem ratio ($p_{FS20} = 0.12$). Fortier's equations were not used to estimate p_{FS2} directly, as their equations are based on trees larger than 2 cm DBH (range = 3.6 to 25.1 cm). Instead, the foliage:stem ratio at DBH = 3.6 was estimated in the same fashion as p_{FS20} ($p_{FS3.6} = 0.45$); then, $p_{FS3.6}$ and p_{FS20} were used to algebraically solve for the coefficients a_p and n_P in the above equation ($a_p = 1.206$; $n_P = -0.771$). Finally, p_{FS2} was calculated from the above equation using these coefficient values and B = 2 ($p_{FS2} = 0.71$).

Table 1. Parameter values for hybrid poplars derived from previously published research.				
Parameter	**3-PG Name**	**Sensitivity Class**	**Hybrid Poplar Value**	**Sources**
Foliage:stem partitioning ratio @ DBH=2 cm	p_{FS2}	H	0.71	[10][a]
Foliage:stem partitioning ratio @ DBH=20 cm	p_{FS20}	H	0.12	[10][a]
Constant in the stem mass v. DBH relationship	a_S	M	0.081	[17][b]
Power in the stem mass v. DBH relationship	n_S	H	2.46	[17]
Maximum fraction of NPP to roots	p_{Rx}	M	0.7	[6]
Minimum fraction of NPP to roots	p_{Rn}	M	0.17	[9] [b]
Mature litterfall rate per month	$gammaF_x$	H	0.10	[4] [b]
Litterfall rate per month at t = 0	$gammaF_0$	L	0.083	[5] [b]
Average monthly root turnover rate	gammaR	L	0.02	[33] [b]
Minimum temperature (°C) for growth	T_{min}	L	10	[31]
Optimum temperature (°C) for growth	T_{opt}	M	30	[8]
Maximum temperature (°C) for growth	T_{max}	L	48	[16]
Value of 'm' when fertility rating (FR) = 0	m_0	L	1	[6][b]
Value of 'fNutr' when FR = 0	fN_0	M	0.26	[41][a]
Power of (1-FR) in 'fNutr'	fN_n	L	1	[41][a]
Max. stem mass (kg/tree) @ 1000 trees/ha	w_{Sx1000}	L	500	[7, 17][a]
Power in self-thinning rule	thinPower	L	-1.45	[7, 17][a]
Specific leaf area (m^2/kg) at age 0	SLA_0	L	19	[8]
Specific leaf area (m^2/kg) for mature leaves	SLA_1	H	10	[17][b]
Extinction coefficient for absorption of PAR by canopy	k	M	0.779	[13]
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	M	0.24	[14]
LAI for maximum rainfall interception	LAImaxIntcptn	L	7.3	[14]
Maximum canopy quantum efficiency (mol C/mol PAR)	alpha	H	0.08	[3]
Ratio NPP/GPP	Y	H	0.43	[18]
Maximum canopy conductance (m/s)	MaxCond	H	0.02	[20]
LAI for maximum canopy conductance	LAIgcx	L	2.6	[20]
Stomatal response to VPD (1/mBar)	CoeffCond	L	0.05	[42][b]
Canopy boundary layer conductance (m/s)	BLcond	L	0.05	[34][b]
Branch and bark fraction at age 0	$frac_{BB0}$	L	0.64	[6]
Branch and bark fraction for mature stands	$frac_{BB1}$	L	0.24	[4][b]
Age (yrs) at which fracBB = (fracBB0+fracBB1)/2	t_{BB}	L	3	[6]
Basic density (t/m^3) for young trees	rhoMin	H	0.39	[23]
Basic density (t/m^3) for older trees	rhoMax	H	0.35	[23]
Age (yrs) at which basic density = (rhoMin+rhoMax)/2	tRho	M	2	[23]
Constant in the stem height relationship	a_H	L	0.036	[7][a]
Power of DBH in the stem height relationship	n_{HB}	L	1.335	[7][a]
Power of stocking in the stem height relationship	n_{HN}	L	0.354	[7][a]
Constant in the stem volume relationship	a_V	L	0.0072	[17][a]
Power of DBH in the stem volume relationship	n_{VB}	L	1.96	[17][a]
Power of stocking in the stem volume relationship	n_{VN}	L	-0.30	[17][a]

Table 1. Parameter values for hybrid poplars derived from previously published research.				
Parameter	**3-PG Name**	**Sensitivity Class**	**Hybrid Poplar Value**	**Sources**

[a] Estimated (algebraically, graphically, or via linear regression) from equations and/or values reported in the literature; see Appendix.
[b] Values reported in the literature have been converted to the units and/or ratios required for model input.

Sources:

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5) Cannell, MGR, Sheppard, LJ, Milne, R (1988) Light use efficiency and woody biomass production of poplar and willow. For 61: 125-136
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7) DeBell, DS, Clendenen, GW, Harrington, CA, Zasada, JC (1996) Tree growth and stand development in short-rotation *Populus* plantings: 7-year results for two clones at three spacings. Biomass Bioenergy 11: 253-269
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13) Green, DS, Kruger, EL, Stanosz, GR, Isebrands, JG (2001) Light-use efficiency of native and hybrid poplar genotypes at high levels of intracanopy competition. Can J For Res 31: 1030-1037
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17) Johansson, T, Karacic, A (2011) Increment and biomass in hybrid poplar and some practical implications. Biomass Bioenergy 35: 1925-1934
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41) van den Driessche, R (1999) First-year growth response of four *Populus trichocarpa* × *Populus deltoides* clones to fertilizer placement and level. Can J For Res 29: 554-562
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Table 2. Parameters assigned intuitive values based on the knowledge and experience of the authors and their collaborators, or an iterative approach for fitting the model.			
Parameter	**3-PG Name**	**Sensitivity Class**	**Assigned Value**
Age in months at which litterfall rate has median value	t_{gammaF}	L	18
Mortality rate (%/yr) for large t	$gammaN_x$	L	0
Seedling mortality rate (%/yr) at t = 0	$gammaN_0$	L	3.5
Age (yrs) at which mortality rate has median value	t_{gammaN}	L	1
Shape of mortality response	n_{gammaN}	L	1
Age (yrs) at which specific leaf area = (SLA0+SLA1)/2	t_{SLA}	L	5
Age (yrs) at canopy cover	fullCanAge	M	5[a]
[a] Parameter value assigned by iterative manipulation to produce best-fit model.			

Table 3. Parameters assigned default 3-PG values.			
Parameter	**3-PG Name**	**Sensitivity Class**	**Default Value**
Days production lost per frost day	k_F	L	0
Moisture ratio deficit for f_q = 0.5	SWconst	H	0.7
Power of moisture ratio deficit	SWpower	L	9
Maximum stand age (yrs) used in age modifier	MaxAge	L	50
Power of relative age in function for fAge	nAge	L	4
Relative age to give fAge = 0.5	rAge	L	0.95
Fraction mean single-tree foliage biomass lost / dead tree	m_F	L	0
Fraction mean single-tree root biomass lost / dead tree	m_R	L	0.2
Fraction mean single-tree stem biomass lost / dead tree	m_S	L	0.2
Intercept of net v. solar radiation relationship (W/m^2)	Q_a	H	-90[a]
Slope of net v. solar radiation relationship	Q_b	H	0.8[a]
Molecular weight of dry matter (dry g/mol)	gDM_mol	H	24[a]
Conversion of solar radiation to PAR (mol/MJ)	molPAR_MJ	H	2.3[a]
[a] Conversion factors; values assumed to be constant.			

Table 4. Summary of climate data for calibration and validation sites.

Site	Temperature and Solar Station ID[a]	Precip. Station ID[b]	Growing Season[c] T_{max} (ºC)	Growing Season[c] T_{min} (ºC)	Mean Annual Precip. (mm y^{-1})	Mean Solar Radiation (MJ m^{-2} d^{-1})
ASH87	14913; 727445	475286	17.7	6.1	807	13.0
ASH88	14913; 727445	475286	17.9	6.4	815	13.0
FRM88	14925; 726586	212698	20.8	9.7	837	13.8
GRF87	14922; 726559	215563	20.8	9.8	662	14.0
GRF88	14922; 726559	215563	20.7	9.8	670	13.9
MIL87	14926; 727475	215392	20.4	7.7	660	13.2
MON87	14991; 726435	475563	21.3	9.1	839	12.9
MON88	14991; 726435	475563	21.4	9.2	843	13.0
CLO88	14913; 727450	211630	17.5	6.9	826	12.9
FAR87	14914; 727530	322859	21.2	8.6	496	13.3
SXF87	14944; 726510	397667	22.5	9.8	605	14.0
SXF88	14944; 726510	397667	22.3	9.8	634	13.9

[a] Temperature and solar radiation data were obtained from the National Renewable Energy Lab (NREL) National Solar Radiation Database (NREL, 2011). The time period (1987-1998) for the plantations in Netzer et al. (2002) is covered by two different datasets (1961-1990 and 1991-2005); thus, the first station ID refers to the 1961-1990 dataset, and the second station ID refers to the 1991-2005 dataset.
[b] Precipitation data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center monthly summaries (NOAA, 2011).
[c] Calculated by averaging monthly temperatures for April through October.

Table 5. Soil texture, depth to water table (D_w), maximum available soil water (ASW_{max}), and minimum available soil water (ASW_{min}) values used for calibration and validation sites.

Site	Soil Texture [a]	D_w (cm) [a]	ASW_{max} (mm) [a]	ASW_{min} (mm)[b]
ASH87	silt loam	30	131	92
ASH88	silt loam	30	131	92
FRM88	clay loam	>100	182	0
GRF87	loam	75	164	41
GRF88	loam	>100	192	0
MIL87	silty clay loam	0	196	196
MON87	silt loam	>100	215	0
MON88	silt loam	>100	211	0
CLO88	loam	>100	163	0
FAR87	silty clay	23	158	122
SXF87	silty clay loam	>100	190	0
SXF88	silty clay loam	>100	181	0

[a] Soil data were obtained from the Natural Resource Conservation Service (NRCS) Web Soil Survey (NRCS, 2011).
[b] Estimated using the Equation 1 (see text).

Table 6. Best-fit values for fertility rating (FR) within the estimated upper and lower limits for age at full canopy closure (fullCanAge), with associated fit statistics.

fullCanAge	FR	Slope	Intercept	R^2	RMSE ($Mg\ ha^{-1}$)
3	0.90	0.99	-3.49	0.873	9.69
4	0.95	0.96	0.46	0.875	8.94
5	1.00	0.95	3.60	0.880	8.77

Table 7. Hypothesized values of fertility rating (FR) and age at full canopy (fullCanAge) by site, based on optimization of fit.

Site	FR	fullCanAge
ASH87	0.85	6
ASH88	0.95	4
FRM88	0.85	6
GRF87	0.90	5
GRF88	0.95	4
MIL87	0.95	4
MON8	0.95	4
MON8	1.00	3
CLO88	0.95	4
FAR87	0.90	5
SXF87	0.85	6
SXF88	0.90	5

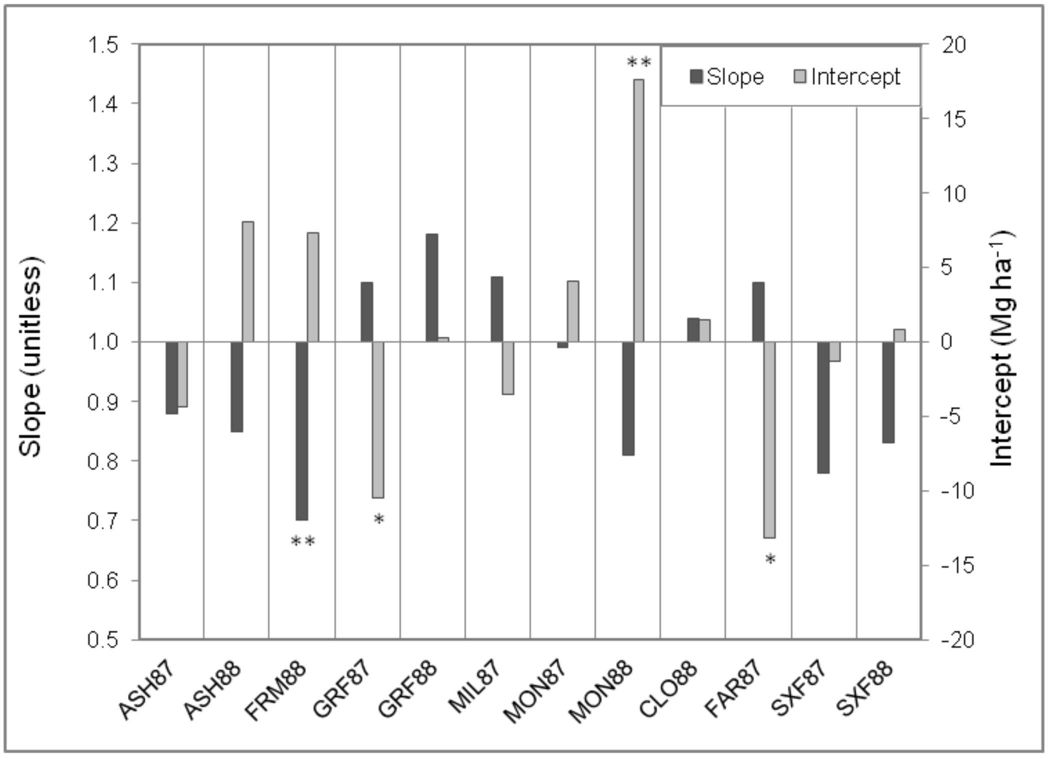


Figure 1. Results of linear regression for predicted biomass versus actual biomass by site. Asterisks represent significant differences at Pr < 0.05 (*), Pr < 0.01 (**), and Pr < 0.001 (***), from contrasts of the surrogate site for the overall model (MON87) versus all other sites.

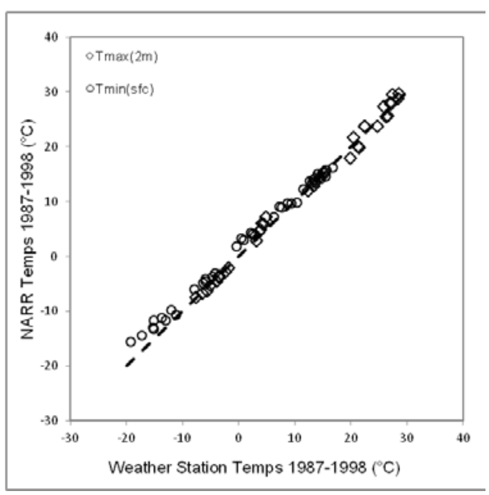


Figure 2. Relationship between weather station data [25] and NARR climate data [26], using the 2-meter dataset for maximum temperatures, Tmax(2m), and the surface dataset for minimum temperatures, Tmin(sfc). Datapoints represent monthly temperatures averaged across the years 1987-1998 for three different locations (Fairmont, Granite Falls, and Milaca, MN); the dashed line represents a perfect 1:1 relationship.

Appendix D: Input and Output Data from 3-PG Modeling

Site	Latitude (°N)	Soil group[a] SSURGO	Soil group[a] Site	Depth to water table (cm)	Available water storage Maximum (mm)	Available water storage Minimum (mm)	T_{opt} (°C)[b] (June-Aug mean max)	Annual Precipitation (mm)	Mean daily solar radiation (MJ m^{-2} d^{-1})	Generalist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (Site) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})
MN1	45.5	SL	SL	15	180	153	25.5	827	17.1	11.1	14.3	14.3
MN2	45.4	SL	SL	>200	180	0	25.5	827	17.1	8.9	10.2	10.2
MN3	45.7	SL	SL	30	180	126	26.4	772	16.8	10.4	12.8	12.8
MN4	45.7	SL	SL	0	190	190	26.4	772	16.8	10.4	12.8	12.8
MN5	45.8	SL	SL	0	200	200	26.2	754	17.2	11.1	13.7	13.7
MN6	45.7	SL	SL	0	150	150	26.2	754	17.2	11.1	13.7	13.7
MN7	45.9	SL	SL	15	110	93.5	26.3	690	17.0	10.7	13.2	13.2
MN8	46.4	SL	S	15	140	119	26.5	672	17.0	10.2	12.5	12.5
MN9	46.4	SL	S	15	140	119	26.5	672	17.0	10.2	12.5	12.5
MN10	46.5	SL	SL	>200	110	0	26.5	672	17.0	7.0	7.9	7.9
MN11	46.9	SL	S	>200	90	0	25.3	629	16.6	6.6	7.9	7.9
MN12	47.0	SL	SL	>200	100	0	25.3	629	16.6	6.7	8.0	8.0
MN13	47.1	SL	SL	75	90	22.5	26.9	605	16.9	6.6	7.4	7.4
MN14	47.1	SL	SL	15	170	144.5	26.9	605	16.9	11.2	13.2	13.2
MN15	47.4	SL	S	15	140	119	27.4	590	16.7	11.2	12.9	12.9
MN16	47.4	SL	SL	40	180	108	26.7	565	16.7	10.8	13.0	13.0
MN17	47.5	SL	SL	40	180	108	26.7	565	16.7	10.8	13.0	13.0
MN18	47.7	S	SL	60	100	40	26.2	537	16.4	8.6	8.3	10.5
MN19	47.8	SL	SL	75	140	35	26.2	537	16.4	5.9	6.8	6.8
MN20	47.9	SL	CL	15	180	153	26.2	503	16.6	10.3	12.7	12.7
MN21	48.0	SL	SL	15	150	127.5	26.2	503	16.6	10.3	12.7	12.7
MN22	48.7	SL	SL	15	170	144.5	26.1	537	16.1	9.3	11.8	11.8
MN23	48.8	SL	SL	15	200	170	25.8	519	16.0	9.1	11.8	11.8
MN24	48.7	SL	SL	76	170	40.8	26.4	553	16.2	6.3	7.4	7.4
MN25	48.5	CL	CL	15	190	161.5	26.4	554	16.2	10.0	12.4	12.4
MN26	48.2	SL	SL	15	180	153	26.4	554	16.2	10.0	12.4	12.4
MN27	47.3	CL	CL	30	190	133	27.6	622	16.7	11.1	12.6	12.6
MN28	46.9	SL	SL	76	200	48	28.0	647	16.8	7.1	7.7	7.7
MN29	46.5	CL	CL	122	170	0	28.2	644	17.0	7.1	7.5	7.5
MN30	46.1	CL	SL	46	180	97.2	28.9	584	17.1	10.8	12.4	11.4
MN31	45.9	CL	SL	0	170	170	27.9	575	17.4	11.6	12.9	12.9
MN32	45.6	SL	CL	60	190	76	28.3	597	17.5	9.0	7.8	9.7
MN33	46.1	SL	SL	15	180	153	26.6	680	17.1	10.5	12.7	12.7
MN34	46.3	SL	SL	76	140	33.6	26.5	672	17.0	6.9	7.7	7.7
MN35	46.2	SL	SL	>200	140	0	26.6	680	17.1	7.0	7.8	7.8
MN36	46.1	SL	SL	15	140	119	26.6	680	17.1	10.5	12.7	12.7

Appendix D: Input and Output Data from 3-PG Modeling

Site	Latitude (°N)	Soil group[a] SSURGO	Soil group[a] Site	Depth to water table (cm)	Available water storage Maximum (mm)	Available water storage Minimum (mm)	T_{opt} (°C)[b] (June-Aug mean max)	Annual Precipitation (mm)	Mean daily solar radiation (MJ m^{-2} d^{-1})	Generalist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (Site) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})
MN37	46.5	SL	SL	15	160	136	26.3	660	16.9	10.4	12.9	12.9
MN38	47.8	SL	CL	15	180	153	26.2	537	16.4	10.1	12.6	12.6
MN39	47.7	SL	SL	>200	180	0	25.5	528	16.4	5.7	6.6	6.6
MN40	47.7	SL	CL	76	160	38.4	25.6	518	16.4	5.6	6.5	6.6
MN41	47.4	SL	SL	76	170	40.8	25.5	584	16.4	5.9	7.2	7.2
MN42	45.7	SL	SL	61	170	66.3	26.7	686	17.2	8.5	9.7	9.7
MN43	45.7	SL	SL	>200	100	0	27.1	676	17.3	7.0	7.7	7.7
MN44	45.7	SL	SL	75	140	35	27.1	676	17.3	7.1	7.7	7.7
MN45	45.0	SL	CL	110	180	0	27.5	733	17.3	7.9	8.5	8.6
MN46	44.4	SL	SL	>200	180	0	27.3	823	17.4	9.4	10.2	10.2
MN47	44.6	SL	SL	61	200	78	27.0	810	17.3	9.9	11.4	11.4
MN48	44.4	SL	SL	110	190	0	27.7	770	17.6	9.1	9.8	9.8
MN49	44.7	CL	SL	45	180	99	27.9	732	17.6	12.0	13.8	13.3
MN50	44.9	CL	CL	75	180	45	27.1	712	17.5	8.4	9.2	9.2
MN51	45.0	CL	CL	75	190	47.5	27.6	662	17.7	7.7	8.3	8.3
MN52	44.8	SL	SL	75	190	47.5	28.2	627	17.8	7.0	7.5	7.5
MN53	44.8	SL	SL	>200	70	0	28.2	627	17.8	7.0	7.5	7.5
MN54	45.1	CL	CL	0	190	190	28.6	586	17.7	12.0	12.9	12.9
MN55	44.8	SL	SL	>200	190	0	29.1	599	17.8	6.2	6.4	6.4
MN56	44.5	SL	CL	>200	180	0	28.9	645	17.8	6.9	7.1	7.2
MN57	44.6	CL	CL	15	180	153	28.2	664	17.8	12.3	13.5	13.5
MN58	44.5	CL	CL	15	180	153	28.0	695	17.9	13.1	14.5	14.5
MN59	44.2	CL	SL	15	180	153	28.0	682	17.9	12.8	14.1	14.1
MN60	44.0	CL	CL	45	180	99	28.0	702	17.9	12.7	14.1	14.1
MN61	43.7	CL	CL	45	190	104.5	27.8	707	18.2	13.0	14.5	14.5
MN62	43.7	CL	CL	15	190	161.5	28.1	649	18.1	12.9	14.2	14.2
MN63	43.9	CL	SL	45	200	110	28.9	599	18.2	11.7	12.8	12.4
MN64	43.5	CL	CL	45	200	110	29.0	623	18.3	12.6	13.2	13.2
MN65	43.7	SL	SL	15	210	178.5	27.5	815	18.0	13.5	15.3	15.3
MN66	44.3	CL	SL	45	170	93.5	27.5	828	17.6	12.7	14.9	14.3
MN67	44.1	CL	CL	15	180	153	26.4	864	17.7	13.0	15.6	15.6
MN68	43.8	CL	SL	15	190	161.5	26.6	892	17.9	13.3	15.9	15.9
MN69	43.6	SL	SL	>200	160	0	26.7	912	18.0	11.8	13.4	13.4
MN70	43.5	SL	CL	30	160	112	26.5	931	17.9	13.2	15.9	15.9
MN71	43.9	CL	CL	0	200	200	26.3	860	17.8	12.6	15.3	15.3
MN72	44.2	SL	SL	>200	210	0	26.2	855	17.7	10.0	11.4	11.4

Appendix D: Input and Output Data from 3-PG Modeling

Site	Latitude (°N)	Soil group[a] SSURGO	Soil group[a] Site	Depth to water table (cm)	Available water storage Maximum (mm)	Available water storage Minimum (mm)	T_{opt} (°C)[b] (June-Aug mean max)	Annual Precipitation (mm)	Mean daily solar radiation ($MJ\ m^{-2}\ d^{-1}$)	Generalist Biomass[c] (SSURGO) ($Mg\ ha^{-1}\ yr^{-1}$)	Specialist Biomass[c] (Site) ($Mg\ ha^{-1}\ yr^{-1}$)	Specialist Biomass[c] (SSURGO) ($Mg\ ha^{-1}\ yr^{-1}$)
MN73	43.9	CL	SL	0	200	200	26.3	865	17.8	12.3	15.1	15.1
MN74	43.9	SL	SL	>200	210	0	26.9	860	17.5	9.8	11.0	11.0
MN75	43.6	SL	CL	>200	200	0	26.3	871	17.8	10.7	12.4	12.4
MN76	47.6	S	na	>200	100	0	25.6	518	16.4	5.5	na	6.7
MN77	48.1	S	na	60	100	40	26.9	557	16.5	9.5	na	11.2
MN78	46.3	SL	na	76	100	24	26.3	660	16.9	7.0	na	7.7
MN79	46.0	SL	na	>200	140	0	26.6	680	17.1	7.0	na	7.8
MN80	45.9	SL	na	>200	180	0	27.1	676	17.3	7.0	na	7.6
MN81	46.0	SL	na	>200	180	0	27.6	622	17.4	6.5	na	6.9
MN82	45.9	CL	na	75	170	42.5	27.9	584	17.4	6.5	na	6.9
MN83	45.8	SL	na	>200	180	0	27.6	622	17.4	6.5	na	6.9
MN84	45.6	CL	na	0	180	180	27.6	609	17.5	11.3	na	12.9
WI1	43.3	SL	SL	137	230	0	26.7	920	17.6	10.6	12.1	12.1
WI2	43.3	SL	SL	122	200	0	26.5	903	17.6	10.7	12.2	12.2
WI3	43.4	SL	SL	61	200	78	26.5	885	17.5	11.1	13.1	13.1
WI4	45.6	S	S	61	70	27.3	23.6	773	16.7	8.5	12.1	12.1
WI5	45.7	SL	SL	60	130	52	23.6	773	16.7	8.2	11.1	11.1
WI6	46.4	SL	SL	0	190	190	22.9	805	16.7	9.1	14.4	14.4
WI7	46.4	SL	SL	76	190	45.6	22.9	805	16.7	8.4	11.6	11.6
WI8	45.0	SL	SL	30	150	105	25.1	799	17.1	10.7	14.2	14.2
WI9	44.9	SL	SL	30	160	112	25.1	799	17.1	10.7	14.2	14.2
WI10	44.9	SL	SL	30	160	112	25.1	855	17.1	10.7	14.2	14.2
WI11	45.0	SL	SL	91	210	18.9	26.0	865	16.9	9.0	10.5	10.5
WI12	45.3	SL	SL	15	210	178.5	24.9	898	17.0	10.2	14.0	14.0
WI13	45.5	SL	SL	30	170	119	24.8	907	16.9	9.8	13.5	13.5
WI14	45.7	SL	SL	76	160	38.4	23.6	845	16.7	8.2	11.1	11.1
WI15	45.6	SL	SL	76	160	38.4	23.6	845	16.7	8.2	11.1	11.1
WI16	44.6	SL	S	15	140	119	25.2	793	17.2	10.8	14.3	14.3
WI17	44.4	SL	SL	>200	120	0	25.4	795	17.3	8.8	10.1	10.1
WI18	45.1	SL	SL	>200	170	0	23.7	796	16.8	8.1	10.5	10.5
WI19	45.2	SL	SL	15	150	127.5	23.7	796	16.8	9.4	14.1	14.1
WI20	45.0	SL	SL	46	210	113.4	26.2	840	17.1	10.6	13.2	13.2
WI21	45.1	SL	SL	76	120	28.8	26.2	840	17.1	8.7	9.7	9.7
WI22	45.5	SL	SL	15	220	187	25.3	860	17.1	10.5	13.9	13.9
WI23	45.6	SL	SL	>200	180	0	24.9	850	17.0	8.6	10.5	10.5

Appendix D: Input and Output Data from 3-PG Modeling

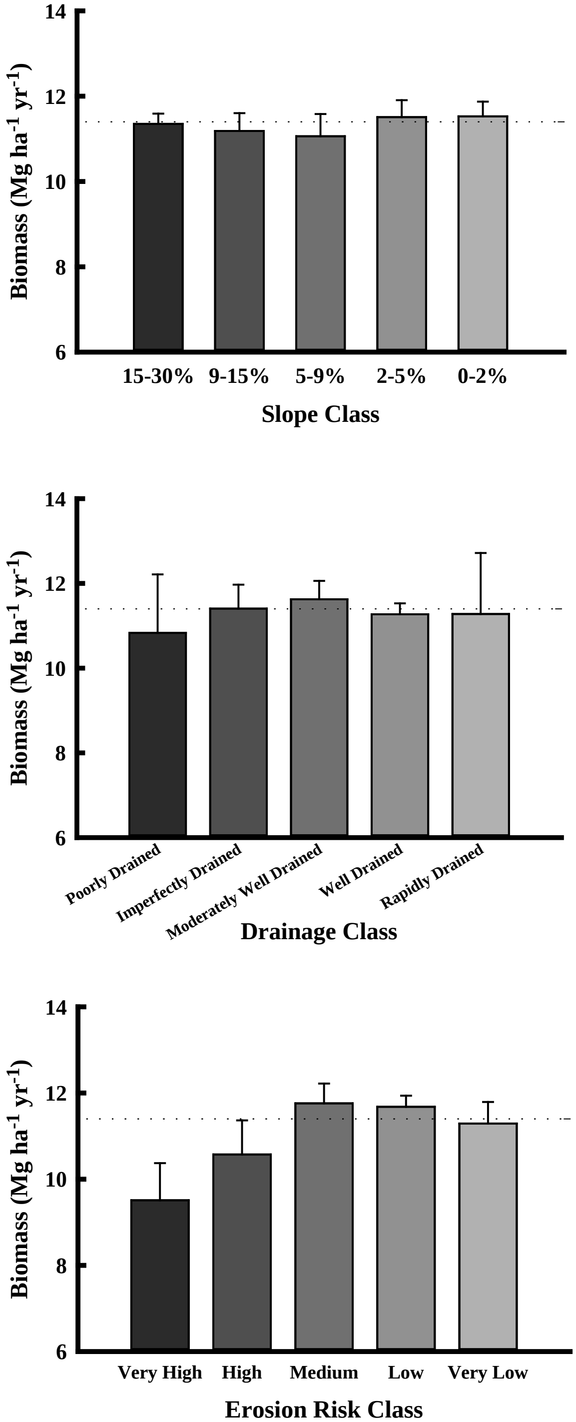
Site	Latitude (°N)	Soil group[a]		Depth to water table (cm)	Available water storage		T_{opt} (°C)[b] (June-Aug mean max)	Annual Precipitation (mm)	Mean daily solar radiation ($MJ\ m^{-2}\ d^{-1}$)	Generalist Biomass[c] (SSURGO) ($Mg\ ha^{-1}\ yr^{-1}$)	Specialist Biomass[c]	
		SSURGO	Site		Maximum (mm)	Minimum (mm)					(Site) ($Mg\ ha^{-1}\ yr^{-1}$)	(SSURGO) ($Mg\ ha^{-1}\ yr^{-1}$)
WI24	45.0	SL	SL	>200	190	0	26.6	853	17.2	9.2	10.4	10.4
WI25	44.8	SL	SL	91	210	18.9	26.6	853	17.2	9.2	10.4	10.4
WI26	44.6	SL	SL	>200	220	0	26.1	884	17.2	9.5	11.0	11.0
WI27	44.5	SL	SL	>200	160	0	26.2	893	17.3	9.8	11.4	11.4
WI28	44.3	SL	SL	>200	200	0	26.2	893	17.3	9.8	11.5	11.5
WI29	44.1	SL	SL	0	250	250	26.5	870	17.4	11.5	13.9	13.9
WI30	43.7	SL	SL	>200	190	0	25.9	907	17.7	11.1	13.2	13.2
WI31	43.6	SL	SL	>200	210	0	26.8	916	17.5	10.2	11.8	11.8
WI32	43.5	SL	SL	>200	140	0	26.6	923	17.5	10.5	12.1	12.1
WI33	43.4	SL	SL	>200	190	0	26.8	913	17.5	10.4	11.9	11.9
WI34	43.0	SL	SL	>200	230	0	27.3	884	17.7	10.2	11.3	11.3
WI35	42.8	SL	SL	>200	230	0	27.3	884	17.7	10.2	11.3	11.3
WI36	42.8	SL	CL	>200	230	0	27.3	884	17.7	10.2	11.3	11.3
WI37	42.7	SL	CL	>200	210	0	27.2	915	17.8	10.5	11.5	11.6
WI38	43.0	SL	SL	153	230	0	27.0	938	17.8	10.8	12.2	12.2
WI39	42.9	SL	SL	>200	80	0	27.0	938	17.8	9.4	10.9	10.9
WI40	42.7	SL	SL	>200	140	0	27.0	940	17.8	10.4	11.7	11.7
WI41	42.6	SL	SL	>200	140	0	27.0	923	17.8	10.5	11.9	11.9
WI42	42.7	SL	SL	102	210	0	26.8	908	17.8	11.0	12.2	12.2
WI43	42.7	SL	SL	102	210	0	26.5	914	17.7	10.8	12.3	12.3
WI44	42.7	SL	SL	102	180	0	26.2	887	17.7	10.9	12.5	12.5
WI45	42.7	SL	C	102	190	0	26.2	887	17.7	10.8	11.9	12.4
WI46	43.4	SL	SL	122	180	0	25.8	882	17.5	10.5	12.4	12.4
WI47	43.6	SL	SL	61	210	81.9	26.1	815	17.4	10.3	12.1	12.1
WI48	43.7	SL	SL	30	210	147	26.1	815	17.4	12.0	14.9	14.9
WI49	43.8	SL	SL	178	200	0	26.3	836	17.3	9.4	10.7	10.7
WI50	43.8	SL	CL	178	150	0	25.4	584	17.1	6.5	7.3	7.5
WI51	43.8	SL	CL	178	150	0	25.4	584	17.1	6.5	7.3	7.5
WI52	43.9	SL	SL	76	190	45.6	25.4	813	17.3	9.5	11.3	11.3
WI53	44.1	SL	CL	15	160	136	25.1	792	17.1	11.9	15.6	15.6
WI54	44.5	SL	SL	178	150	0	24.8	755	17.0	8.7	10.5	10.5
WI55	44.6	SL	CL	15	170	144.5	25.2	749	16.9	10.9	14.3	14.3
WI56	44.3	S	SL	>200	100	0	26.2	792	17.0	8.4	9.6	9.5
WI57	44.5	SL	SL	178	160	0	25.8	777	17.0	8.7	10.0	10.0
WI58	42.8	SL	SL	>200	190	0	27.3	872	17.7	10.2	11.4	11.4

Appendix D: Input and Output Data from 3-PG Modeling

Site	Latitude (°N)	Soil group[a] SSURGO	Soil group[a] Site	Depth to water table (cm)	Available water storage Maximum (mm)	Available water storage Minimum (mm)	T_{opt} (°C)[b] (June-Aug mean max)	Annual Precipitation (mm)	Mean daily solar radiation (MJ m^{-2} d^{-1})	Generalist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (Site) (Mg ha^{-1} yr^{-1})	Specialist Biomass[c] (SSURGO) (Mg ha^{-1} yr^{-1})
WI59	44.5	SL	SL	>200	210	0	26.5	858	17.3	9.2	10.5	10.5

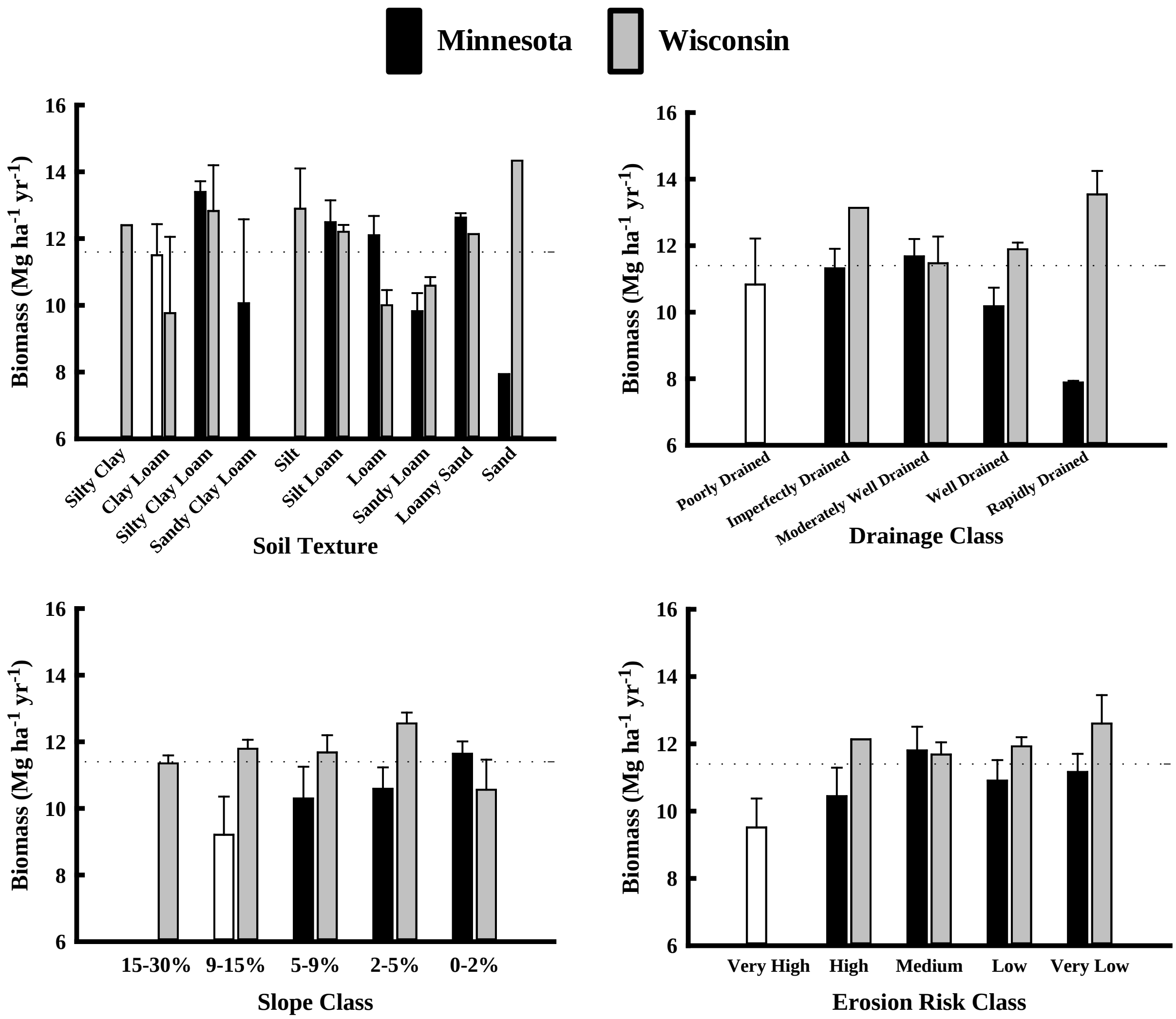
na=not available.
[a]See Table 1 for the classification scheme for assigning soils to default 3-PG soil classes.
[b]Optimum temperature for photosynthesis, according to Drew and Chapman (1992).
[c]See Materials and Methods for details about the three yield scenarios tested with 3-PG.

Appendix E: Predicted Poplar Biomass for Soil Classes (Across States)



Predicted poplar yield for slope, drainage and erosion risk classes across Minnesota and Wisconsin, USA. The dashed line is the overall mean. See Materials and Methods for descriptions of the soil classes.

Appendix F: Predicted Poplar Biomass for Soil Classes (Within States)



Predicted poplar yield for soil texture, as well as drainage, slope, and erosion risk classes for Minnesota and Wisconsin, USA. The dashed line is the overall mean. See Materials and Methods for descriptions of the classes.