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An approach for siting poplar energy production systems to increase productivity and associated ecosystem services

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ABSTRACT

Short rotation woody crops such as *Populus* spp. and their hybrids (i.e., poplars) are a significant component of the total biofuels and bioenergy feedstock resource in the USA. Production of these dedicated energy crops may result in large-scale land conversion, which leads to questions about their economic, logistic, and ecologic feasibility. To address such concerns, we used available social (i.e., land ownership and cover) and biophysical (i.e., climate and soil characteristics) spatial data to map eligible lands suitable for establishing and growing poplar biomass for bioenergy crops across Minnesota and Wisconsin, USA. We confirmed the validity of this mapping technique by sampling and assessing biotic variables within locations identified on the maps. Lastly, we estimated potential poplar productivity within identified areas using a process-based growth model (3-PG) to determine spatial distribution of productive lands across the study area. Overall, eligible lands suitable for poplar production systems totaled 373,630 ha across both states, representing 30.8% of the study area and a total potential aboveground yield at the end of a 10-year rotation of 36.2–42.6 dry Tg. Poplar biomass ranged from 9.5 ± 0.3 to 11.9 ± 0.2 dry Mg ha^{-1} yr^{-1} across both states, with an overall mean of 10.0 ± 0.1 dry Mg ha^{-1} yr^{-1}. 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. 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.

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1. Introduction

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). Woody perennial crops have the potential to be a significant component of the total biofuels produced in the USA, and are estimated to be the second most available biomass resource in this country (NAS, 2009; US DOE, 2011). Poplars (*Populus* spp. and their hybrids) are cosmopolitan across North America, and have been identified as a potentially large source of renewable energy feedstocks (Stanton et al., 2002; Tharakan et al., 2003; US DOE, 2011). 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). Productivities of intensively-managed poplar plantations (IMPPs) are commonly near 10 dry Mg ha^{-1} yr^{-1} (generalists), with values approaching 20 dry 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. The primary growers of IMPPs in the future will likely be current farmers; therefore, converting their agricultural or marginal land into IMPPs will require that it be economically feasible (Husain et al., 1998; Walsh et al., 2003; Lazarus et al., 2011). Likewise, these dedicated

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woody crop production systems will only work if they are logistically practical – i.e., if transportation to the mill does not affect the ability to sell the crop (Gan and Smith, 2011). Finally, IMPPs must be ecologically sustainable. Farmers would likely not wish to convert land into a crop that degrades the environment, potentially increasing their liability by impacting water and soil quality in their community (Neumann et al., 2007).

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 abiotic data, we can identify potential areas to establish IMPPs that have a high probability of success. One such model for predicting poplar growth is the Physiological Processes Predicting Growth (3-PG) model (Landsberg and Waring, 1997). This model considers soils and climate data, as well as parameters derived from empirical growth data, for a specific tree species (Sands and Landsberg, 2002). The 3-PG model has already been calibrated to predict hybrid poplar growth in Canada (Amichev et al., 2010) and the upper midwestern USA (Headlee et al., 2012).

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. Therefore, our first objective was to 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 for bioenergy crops across Minnesota and Wisconsin, USA (see Malczewski, 2004). Our second objective was to confirm the validity of this mapping technique by sampling and assessing biotic variables within locations identified on the maps. Our final objective was to estimate potential poplar productivity within identified areas using 3-PG to determine spatial distribution of productive lands across the study area. To our knowledge, this is the first attempt at integrating large-scale biophysical spatial data and local-site information with 3-PG growth productivity modeling to assess where IMPPs can be established and grown. 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 (e.g., provisioning services: biomass; regulating services: erosion control, soil quality maintenance; supporting services: nutrient/water cycling), and is widely applicable to woody biomass production systems worldwide.

2. Materials and methods

2.1. Overview

We identified, in a spatially-explicit manner, a continuum of suitable areas within Minnesota and Wisconsin, USA for potential poplar establishment and development by combining key climatic and soil properties with land ownership and use constraints, which are described in detail below. Specifically, we used a stepwise approach to: (1) identify eligible lands suitable for poplar deployment based on current land use, land ownership, and local soil characteristics, (2) determine temperature–precipitation gradients important to the growth of poplars, (3) establish sites for field reconnaissance within the suitable lands, (4) assess the validity of the outcomes from (1) and (2) by comparing available databases with field soils data (i.e., QA/QC), and (5) apply a process-based growth model (3-PG) to predict and map poplar productivity within the identified suitable lands.

2.2. Identifying eligible 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 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 (Fig. 1).

We obtained land cover data from the 2006 National Land Cover Database (NLCD) classification scheme of the US 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.

We acquired land ownership data from the USGS Upper Midwest Gap Analysis Program (UMGAP), Minnesota and Wisconsin stewardship programs (USGS, 2005). We excluded public lands (i.e., those classified as federal, state, county, and tribal) from the base layer.

We obtained soil property variables from the Soil Survey Geographic database (SSURGO, 2012). 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, respectively. The muaggatt table reports a variety of soil attributes and their interpretations; the chtexturegrp table details individual textures for each soil horizon. 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 $\geqslant 14$ 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). Lastly, we assembled and queried spatial datasets using Spatial Analyst within ArcGIS software (ESRI, Inc., Redlands, CA, USA).

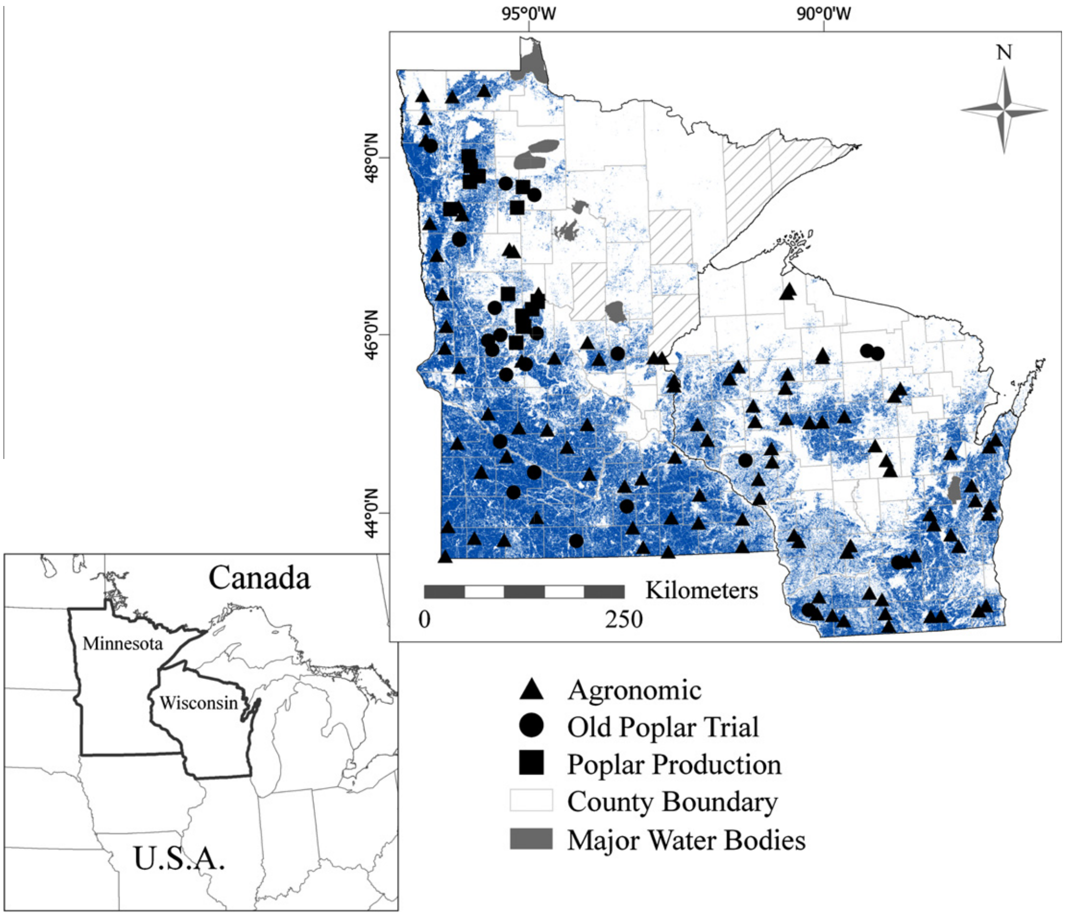

Fig. 1. Study site locations across Minnesota and Wisconsin, USA superimposed on eligible lands suitable for IMPP establishment and growth (blue area). Suitability of lands within the gray hatched areas was not assessed due to lack of soil spatial data.

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.

2.3. 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; NCDC, 2011) 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-h 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-h 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-h 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-h increment. To calculate the 10-year average accumulated precipitation for all months individually, we summed the 3-h 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-h 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-year average

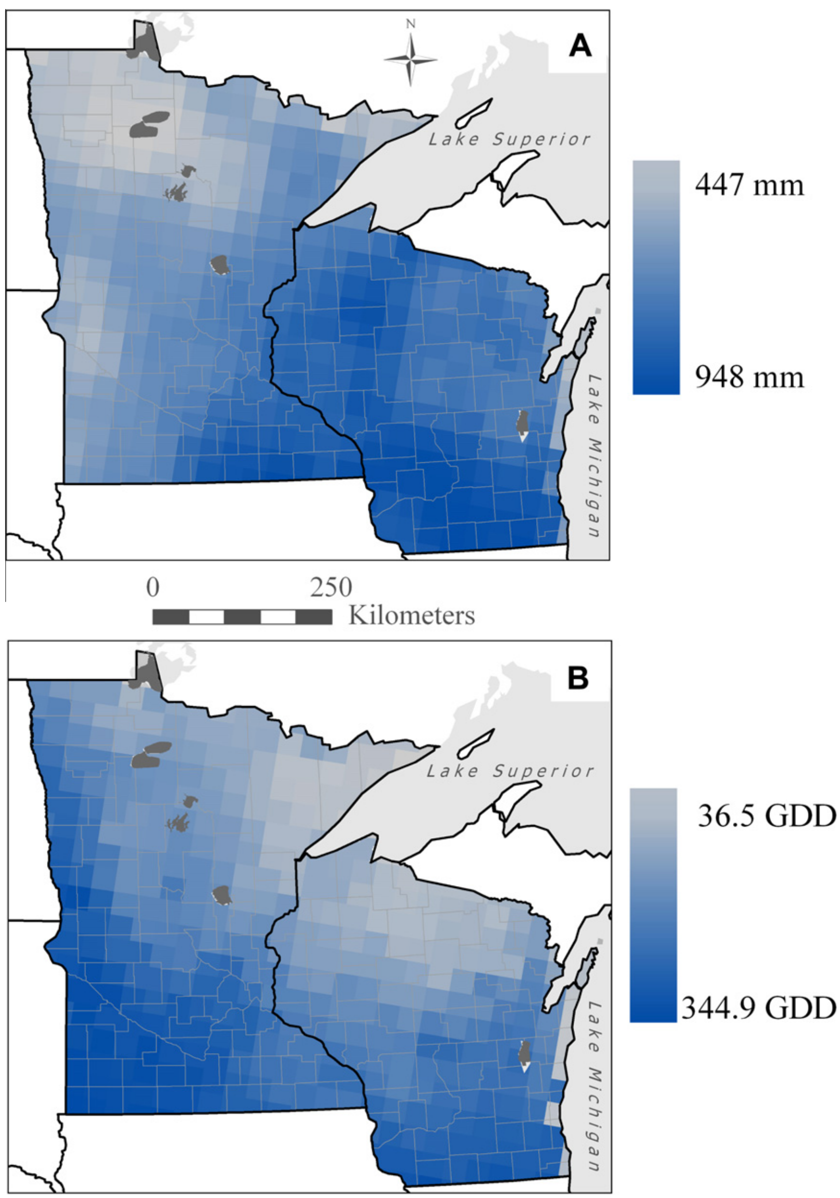

Fig. 2. Average total annual precipitation (A) and average total annual growing degree days (B) for Minnesota and Wisconsin, USA (1999–2008). See Section 2 for a description of how growing degrees days were calculated.

downward shortwave radiation flux for each month was calculated by averaging the eight 3-h 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 et al., 2006). These attributed grids demonstrate the gradients in temperature and precipitation across the land base (Fig. 2). Growing degree days (GDDs) 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-h 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.

2.4. Field reconnaissance and 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 (e.g., fertility, water holding capacity, erosion mitigation), 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 US Department of Energy testing network established in 1988–1991 (Netzer et al., 2002), 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. We also characterized the overall suitability of sites for trees.

We collected soil samples at three locations separated by at least 10 m at each site. Specifically, we harvested one soil sample (3.8 cm dia.) to a 30 cm depth from each sample point using a stainless steel soil core sampler with a plastic liner (AMS Inc., American Falls, ID, USA). In the field, we performed qualitative assessments for soil structure and presence of horizons and/or gleying at the bottom of the cores. After collection, we held samples at ambient temperature until returning to the US Forest Service, Institute for Applied Ecosystem Studies in Rhinelander, WI, USA. We stored the soils at 5 °C until carefully removing them from the plastic liners. After removal, we archived one half of each sample (from ground level to 30 cm depth) at the Rhinelander Laboratory and composited the other half to produce one sample per study site (i.e., we bulked half of the soil from each of the three samples per site). We then air-dried the composited soil samples and hand-crushed them to pass through a 2 mm mesh screen, before sending them to the University of Wisconsin Soil Testing Laboratory in Verona, WI, USA for soil texture determination. We also similarly sieved the archived samples, ground them through a 0.5 mm screen using a Cyclotec 1093 grinder (FOSS Analytical A/S, Eden Prairie, MN, USA), and analyzed them 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 (N) and carbon (C) 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). We calculated cation exchange capacity (CEC) by summing the base cations, and we determined effective cation exchange capacity (ECEC) 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.

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

	Description
Drainage class	
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	
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

2.5. 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, we evaluated success rates non-parametrically using a Chi-square (χ^2) 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, we split the agronomic sites into annual and perennial groups, and combined the two poplar cover types. Thus, we tested for differences among annual, perennial, and poplar land cover. Furthermore, we combined empirical data from prior regional field testing networks (Riemenschneider et al., 2001; Netzer et al., 2002; Zalesny et al., 2009) with the process-based productivity modeling described below to predict establishment and long-term yield of favorable genotypes throughout the eligible lands.

2.6. 3-PG model development and productivity mapping

In addition to identifying suitable lands, several of the climate and soil variables described above can be used to estimate poplar productivity in the process-based model 3-PG (Landsberg and Waring, 1997). To model a given species, 3-PG requires site-level climate and soil data, as well as species-specific physiological parameters which dictate tree growth in response to these site-level variables (Sands, 2004). This model has been used successfully to predict hybrid poplar growth in Canada (Amichev et al., 2010) and across sites in Minnesota and Wisconsin (Headlee et al., 2012); we used physiological coefficients from the latter in the current study. Likewise, we used the same methods as Headlee et al. (2012) (see below for brief description), but with SSURGO rather than STATSGO soil data; this provided similar results at the state level but greater resolution at the county level. We retrieved soil parameters for use in 3-PG 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-m 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 (Headlee et al., 2012).

For all sites, we assumed a planting density of 1736 trees per hectare and rotation age of 10 years, as well as a fertility rating (FR) = 1 and age at full canopy cover (fullCanAge) = 5 years. We tested three yield scenarios with 3-PG; one simulating yields with generalist clones (i.e., the default settings for poplar developed by Headlee et al., 2012), 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 *Populus trichocarpa*, *Populus 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. We conducted analyses of variance (ANOVAs) to test for differences among the three simulations assuming a completely randomized design with state and genotype group (i.e., simulation) main effects and their interaction comprising the model (SAS Institute Inc., 2004). Similarly, using the SSURGO simulation for specialist clones, we subjected productivity values to independent ANOVAs for soil texture, drainage class, slope class, and erosion risk. We tested state and soil class main effects, along with their interaction. We used Fisher's protected least significant difference (LSD) to compare all means, which we 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. We used the scenario of specialist clones with SSURGO data for this purpose; as such, the estimates should be treated as the maximum potential productivity 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, we used these soils values to estimate biomass productivity for each soil texture group in each climate cell using 3-PG. We then averaged these soil-group estimates (weighted by area) within each cell to produce a single estimate of productivity for each climate cell. Lastly, we overlaid this productivity layer 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), we used temperature data from the next-closest inland cell (Headlee et al., 2012). 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 (Headlee et al., 2012). We did not attempt the latter 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. We estimated productivity for each soil map unit (polygon) using the soil and climate variables described above. If a soil polygon crossed climate cells, we divided it and estimated productivity for each section separately using the climate cell values within which the polygon was contained. Similar to the two-state map, we then overlaid this productivity layer with the suitable lands layer to show productivity estimates for those lands suitable for afforestation at the 30-m resolution.

3. Results

3.1. 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 (Fig. 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 (Fig. 1), but the predominance of public lands in much of these areas excluded the lands from being eligible for establishing IMPPs.

3.2. Field site information

A total of 143 sites were sampled: 84 in Minnesota and 59 in Wisconsin (Fig. 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 (Fig. 3). Pooled data indicated that silt loam and sandy loam were the most common soil types in our study areas (Fig. 3). Study sites in Minnesota were less sloped than Wisconsin, but overall most slopes were 5% or less (Fig. 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 >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.

3.3. 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

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.

State(s)	Drainage		Erosion	
	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

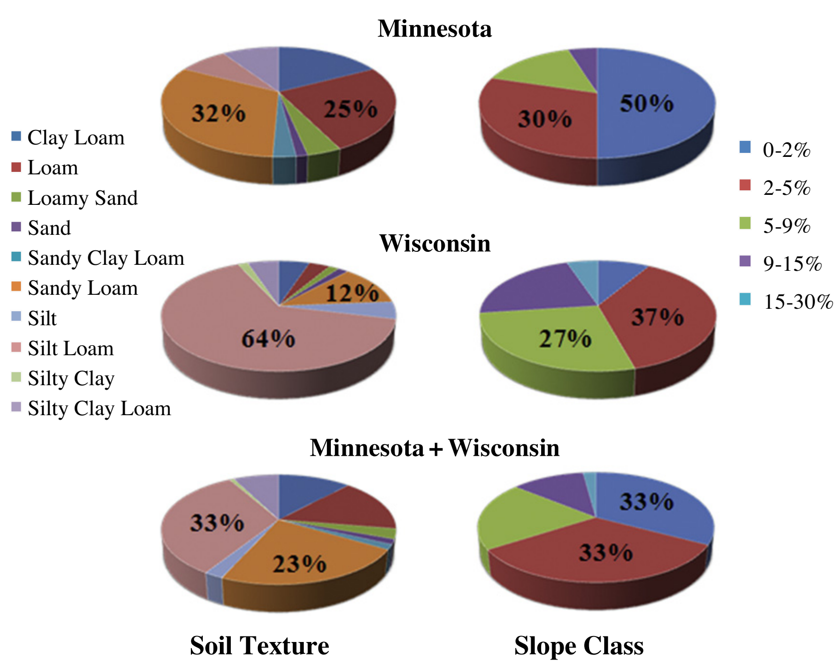

Fig. 3. Soil texture and slope class across study sites in Minnesota and Wisconsin, USA.

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.

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

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 ($P_{strict} = 0.2060$; $P_{loose} = 0.3044$).

3.4. 3-PG model development and productivity mapping

Input and output data for the 3-PG modeling are found in Appendix C. Poplar biomass ranged from 9.5 ± 0.3 to 11.9 ± 0.2 dry Mg ha^{-1} yr^{-1} for all three productivity scenarios across both states, with an overall mean of 10.0 ± 0.1 dry 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 dry Mg ha^{-1} yr^{-1}) was significantly greater than in Minnesota (10.6 ± 0.2 dry 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 dry 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 dry Mg ha^{-1} yr^{-1} (silty clay loam) across textures, with an overall mean of 11.6 ± 0.2 dry Mg ha^{-1} yr^{-1} (Fig. 4). Soils comprised of substantial components of silt had greater overall predicted biomass, while those with sand exhibited the least. Furthermore, predicted biomass for the three remaining landscape variables was different between Minnesota and Wisconsin ($P_{slope} = 0.0241$, $P_{drainage} = 0.0105$, $P_{erosion} = 0.0298$) 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 dry Mg ha^{-1} yr^{-1}) and drainage class (0.8 dry Mg ha^{-1} yr^{-1}), but varied most for erosion risk class (2.3 dry Mg ha^{-1} yr^{-1}) (Appendix D). In contrast, the predicted biomass between states was most stable for erosion risk relative to the other soil classes evaluated (Appendix E).

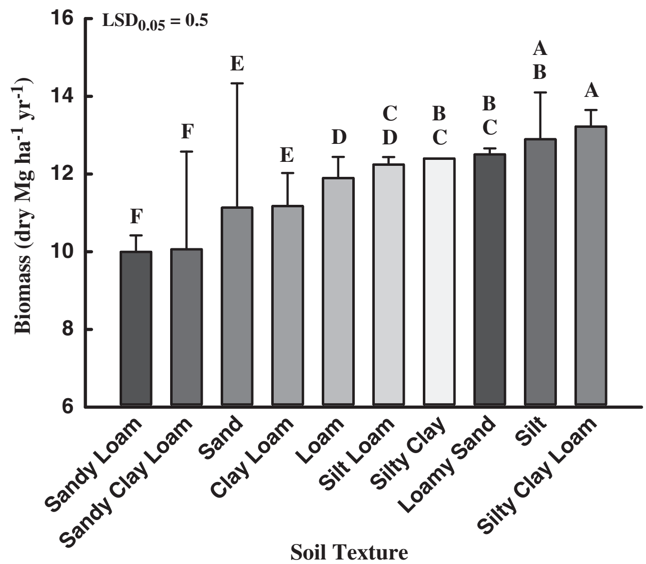

Fig. 4. Predicted poplar productivity on different soil textures in Minnesota and Wisconsin, USA. Standard error bars represent one standard error of the mean. Bars labeled with different letters are different according to Fisher's protected least significant difference at $P < 0.05$.

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 south-central 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.

Table 5
Total standing aboveground dry biomass (Tg) of natural forests on private lands in Minnesota and Wisconsin, USA (2007–2011; DBH > 2.54 cm) (data from Woudenberg et al., 2011) (A) and potential of poplar on suitable lands at the end of a 10-year rotation as predicted using three yield scenarios with 3-PG (B).

	Minnesota	Wisconsin	Minnesota + Wisconsin
(A)			
Tree species group			
Cottonwood and aspen	44.0	33.4	77.5
Noncommercial hardwoods	3.0	4.8	7.9
Commercial hardwoods[a]	130.7	295.5	426.2
Softwoods[b]	34.4	68.1	102.5
Total	212.2	401.8	614.0
(B)			
Yield Scenario[c]			
Generalist (SSURGO)	23.7	12.1	36.2
Specialist (Site)	28.2	14.7	43.3
Specialist (SSURGO)	27.5	14.7	42.6

[a] Commercial hardwood species include: ash, basswood, beech, black walnut, hard maple, hickory, red oaks, soft maple, white oaks, and yellow birch (Woudenberg et al., 2011).
[b] Softwood species include: balsam fir, eastern hemlock, eastern white and red pines, jack pine, and spruces (Woudenberg et al., 2011).
[c] See Section 2 for details about the three yield scenarios tested with 3-PG.

4. Discussion

4.1. Potential contribution of IMPPs to regional biomass supplies

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).

It is also meaningful to compare the predicted aboveground poplar biomass yield at rotation age (i.e., 10 years) from our model with standing aboveground biomass in natural forests of Minnesota and Wisconsin to gauge the potential contribution of IMPPs to overall biomass availability in these states. The total potential aboveground dry biomass of IMPPs in Minnesota plus Wisconsin ranged from 36.2 to 43.3 dry Tg at the end of a 10-year rotation, with a mean of 40.7 dry Tg across all 3-PG scenarios (Table 5). In general, 65% of the poplar biomass could be produced in Minnesota and 35% in Wisconsin. To be consistent with our primary constraint of excluding public lands from our model, the standing biomass in natural forests on private lands within these states is 614 dry Tg, with 35% growing in Minnesota and 65% in Wisconsin (Table 5). The poplar yield at the end of a 10-year rotation was estimated to be 47% of the standing cottonwood and aspen biomass, which is important given the substitution of poplar wood for that of cottonwood and aspen in energy and fiber applications (Stanton et al., 2002). Although IMPPs would not be grown in lieu of hardwoods in either state, it is also worth noting that the yield of poplars was estimated to be nearly five times that of current noncommercial hardwood biomass, which is a potential source of feedstock for the energy industry. Overall, these poplar biomass projections agree with previous reports, that IMPPs can be used to reduce pressure on native forests (Gladstone and Ledig, 1990; Joslin and Schoenholtz, 1997).

4.2. Productivity

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

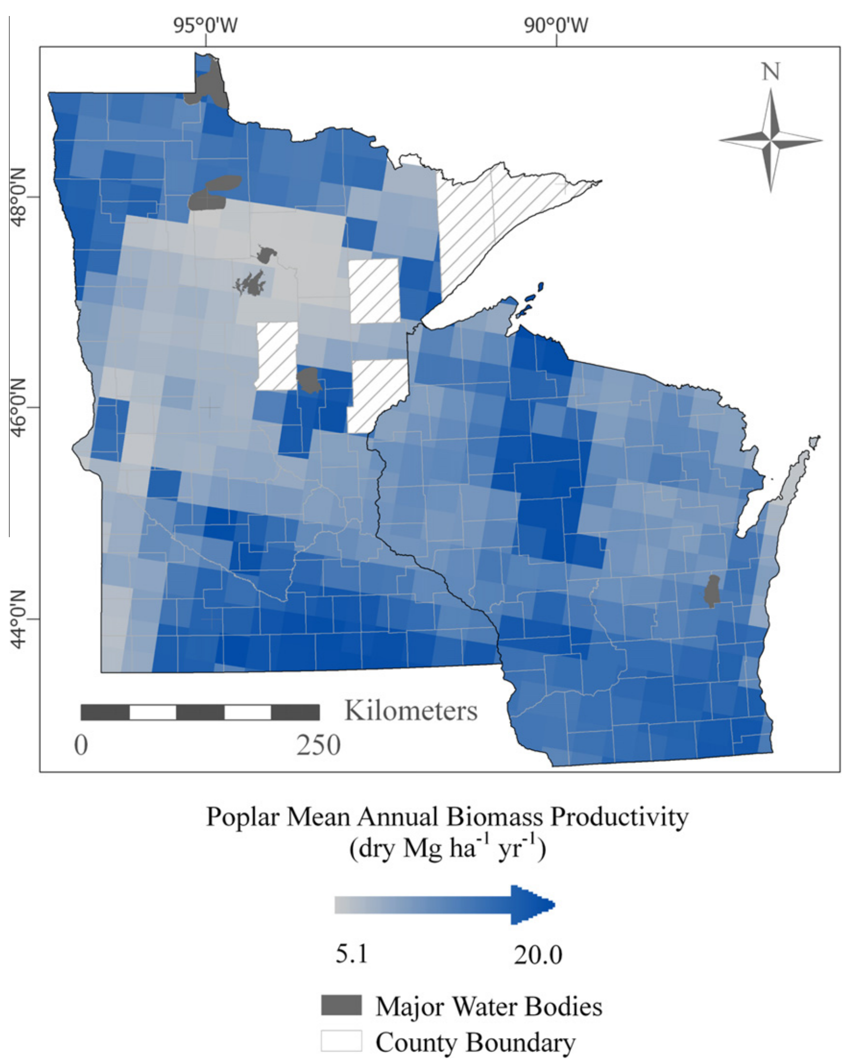

Fig. 5. Predicted poplar productivity across Minnesota and Wisconsin, USA, assuming SSURGO soils data and specialist genotypes that are matched to ideal site conditions. Productivity is shown at 32 × 32 km resolution. Due to lack of soil spatial data, it was not possible to predict productivity within the gray hatched areas.

characteristics in 3-PG modeling results (Dye et al., 2004). Productivity estimates for the specific field sites were significantly influenced by soil texture (Fig. 4), but were not significantly affected by the other variables evaluated (drainage class, slope class, and erosion risk; Appendix D), 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 productivity reductions predicted for the higher slope (5–30%) 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 productivity. Similarly, texture may explain the predicted biomass 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 biomass. 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 (FR) 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.

While setting the FR in 3-PG at its maximum value (FR = 1) has been shown to produce the suitable predictions for poplar plantations established on agricultural lands in the region (Headlee et al., 2012), it should be noted that soil fertility varies by site and also may decline over time with continuous production of IMPPs. Thus, the estimates presented here should be considered as representative of potential productivities under optimal nutrient conditions, and it should be recognized that maintaining optimal nutrient conditions is likely to require fertilizer inputs. Nitrogen fertilization at mid-rotation (i.e., canopy closure) can be particularly effective for maintaining high productivity (Coleman et al., 2006), and carries the advantage of reducing the off-site impacts of fertilization by ensuring the site is well-occupied by the trees. Thus, careful monitoring of soil fertility and well-timed fertilizer applications can help to ensure the long-term productivity and sustainability of IMPPs.

Overall, productivity estimates (Figs. 5 and 6) were similar to those generated by Headlee et al. (2012), with the primary difference being an overall increase in biomass 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 (Headlee et al., 2012), 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 (Fig. 2B) and the high productivity areas in central Wisconsin may be a result of

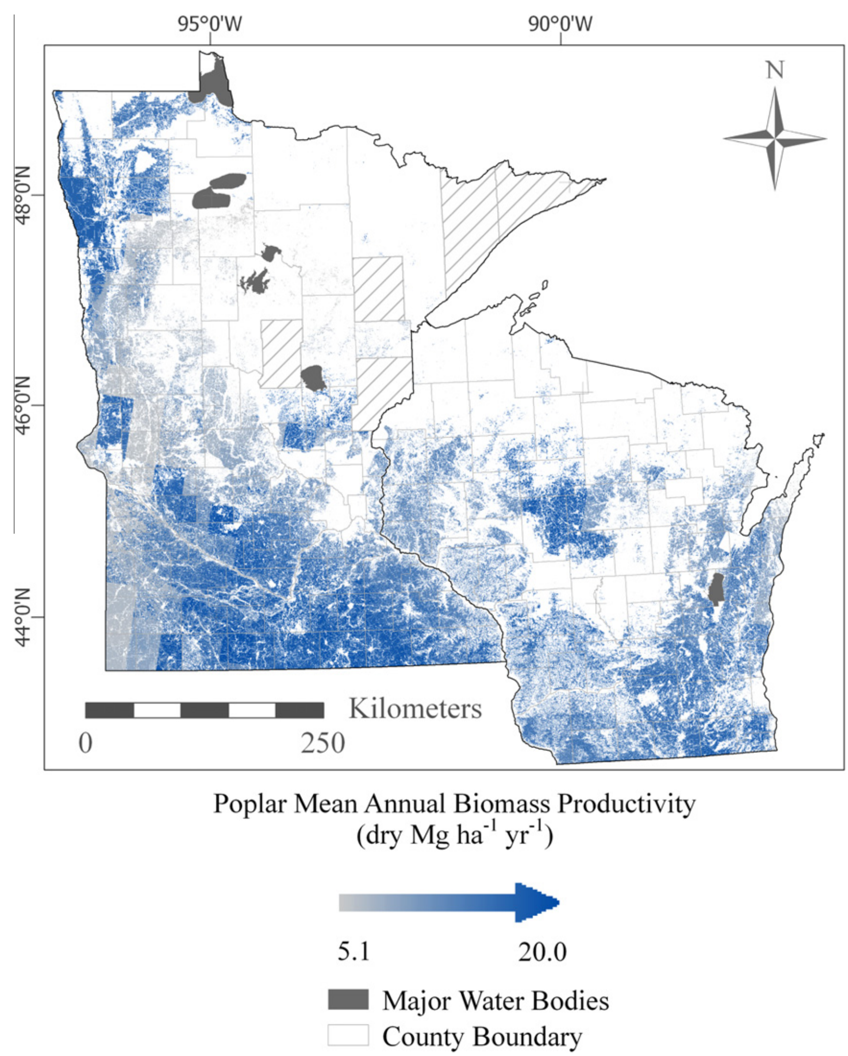

Fig. 6. Predicted poplar productivity within the suitable land base, assuming SSURGO soils data and specialist genotypes that are matched to ideal site conditions. Productivity is shown at 32 × 32 km resolution. Due to lack of soil spatial data, it was not possible to predict productivity within the gray hatched areas.

greater precipitation patterns in those areas (Fig. 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 productivities 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 predictions.

The effects of water table access are also illustrated in the productivity map for Douglas County (Fig. 7). In general, the areas with predicted productivities greater than 10 dry Mg ha^{-1} yr^{-1} have water tables that reach within the top meter of soil, whereas the areas with less than 10 dry Mg ha^{-1} yr^{-1} have water tables that stay below the top meter. Linear regression of the data confirmed that predicted productivity 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 productivities in counties having higher precipitation.

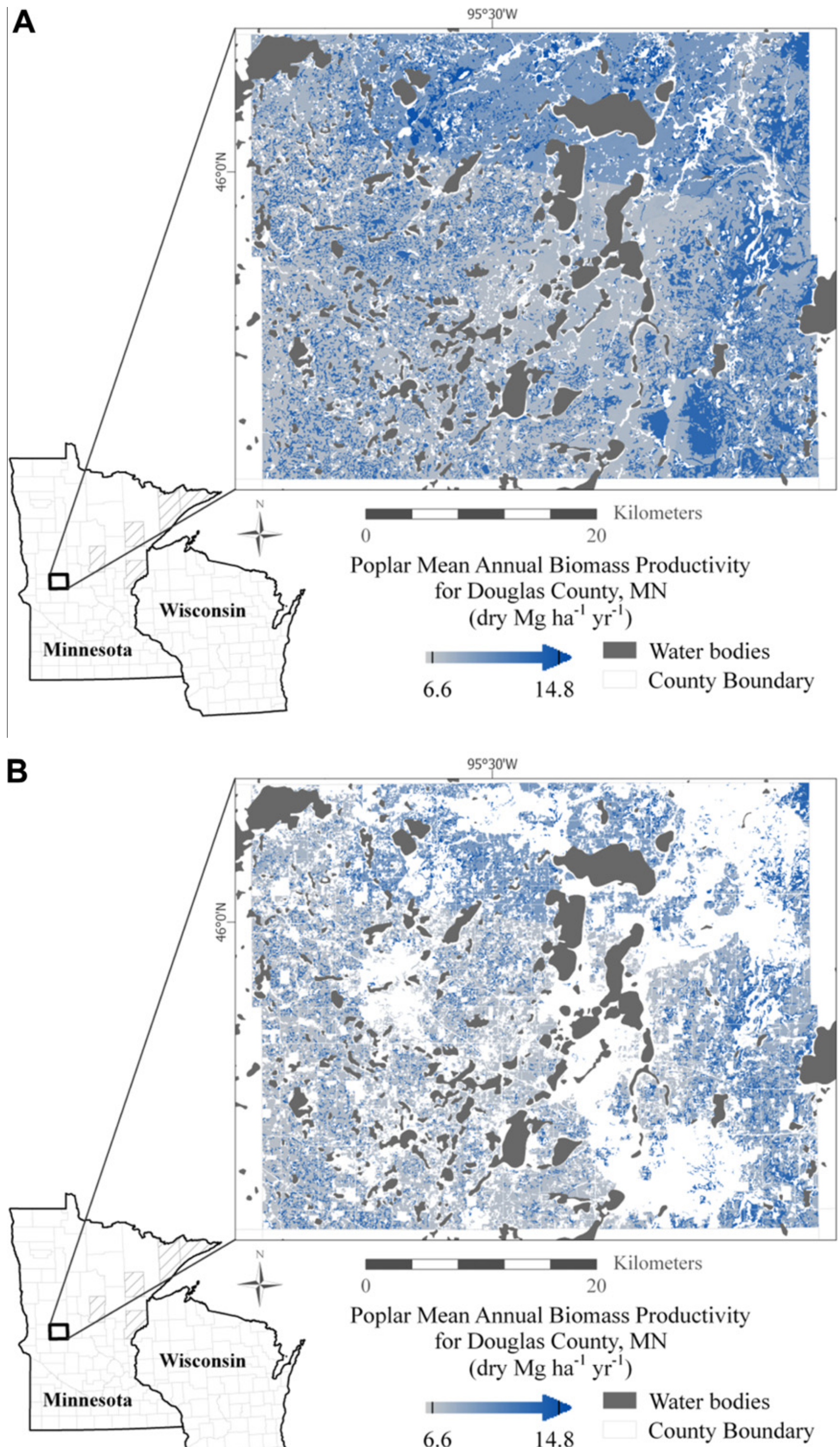

Fig. 7. Predicted poplar productivity throughout (A) and on suitable lands within (B) Douglas County, Minnesota, USA, assuming SSURGO soils data and specialist genotypes that are matched to ideal site conditions. Productivity is shown at 30 × 30 m resolution.

4.3. Site suitability

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 (Fig. 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 land base. 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 were 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 (Fig. 5). Not surprisingly, these attributes are part of what make Minnesota and Wisconsin such agriculturally productive states.

4.4. Genotype × environment interactions

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 3–58%), 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 7–10 years after planting. Similarly, Riemenschneider et al. (2001) reported a 50% advantage for the five best clones at 6 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, 1999; Tschaplinski et al., 1998) and can be exploited given the use of our integrated approach and proper clonal selection.

5. Conclusions

One of the most substantial knowledge gaps with IMPPs worldwide is the lack of comprehensive productivity and yield data throughout plantation development and at rotation age, and this trend is also apparent in the United States. Understanding genotype × environment interactions would enhance yields throughout Minnesota and Wisconsin, yet current data needs are not being adequately met by continued breeding and regional testing networks. For example, there are only two remaining active poplar breeding programs in the United States, which is substantially less than the fourteen taking place in 1987 (Hall et al., 2011). If such information was available, however, estimates in our current model would be greatly refined by adding more sites and genotypes at the calibration and validation steps. This is important because the potential negative 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 is a first critical step towards fulfilling such objectives.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.07.022.

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