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Using a Process-Based Model (3-PG) to Predict and Map Hybrid Poplar Biomass Productivity in Minnesota and Wisconsin, USA

William L. Headlee · Ronald S. Zalesny Jr. · Deahn M. Donner · Richard B. Hall

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Abstract Hybrid poplars have demonstrated high biomass productivity in the North Central USA as short rotation woody crops (SRWCs). However, our ability to quantitatively predict productivity for sites that are not currently in SRWCs is limited. As a result, stakeholders are also limited in their ability to evaluate different areas within the region as potential supply sheds for wood-based bioenergy facilities. A reliable method for predicting productivity across the region is needed; preferably, such a method will also lend itself to generating yield maps that stakeholders can use to inform their decision making. In this study, the Physiological Processes Predicting Growth model was (1) assigned parameters for hybrid poplars using species-specific physiological data and allometric relationships from previously-published studies, (2) calibrated for the North Central region using previously-published biomass data from eight plantations along with site-specific climate and soils data, (3) validated against previously published biomass data from four other plantations using linear regression of actual versus predicted total aboveground dry biomass (R^2=0.89, RMSE=8.1 Mg ha^{-1}, mean bias=5.3 Mg ha^{-1}), (4) evaluated for sensitivity of the model to manipulation of the parameter for age at full canopy cover (fullCanAge) and the fertility rating growth modifier, and (5) combined with soil and climate data layers to produce a map of predicted biomass productivity for the states of Minnesota and Wisconsin. Mean annual biomass productivity (total aboveground dry biomass divided by age) ranged from 4.4 to 13.0 Mg ha^{-1} year^{-1} across the states, with the highest productivity mainly concentrated in the area stretching from south-central Minnesota across southern Wisconsin.

Keywords 3-PG · Geographic information system · *Populus* · Site quality · Yield

W. L. Headlee (✉) · R. B. Hall
Department of Natural Resource Ecology & Management,
Iowa State University,
339 Science 2,
Ames, IA 50011-3221, USA
e-mail: wheadlee@iastate.edu

R. S. Zalesny Jr. · D. M. Donner
US Forest Service, Northern Research Station,
Institute for Applied Ecosystem Studies,
5985 Highway K,
Rhinelander, WI 54501, USA

Introduction

Short rotation woody crops (SRWCs) are purpose-grown trees that are an integral component of the USA's potential woody biomass supply for bioenergy and biofuels; as such, the production of woody crops on agricultural lands (in addition to herbaceous perennials) is expected to expand to 346 million Mg of dry biomass annually by the year 2030 [1]. These trees are environmentally and economically sustainable and very productive. In fact, mean annual biomass productivity of up to 10 Mg ha^{-1} year^{-1} is attainable on marginal lands [2], and those approaching 20 Mg ha^{-1} year^{-1} are possible when growing adapted genotypes at sites with optimal climatic and environmental conditions [3, 4].

Trees belonging to four genera comprise the majority of SRWCs grown in the USA: *Populus* (cottonwoods, poplars, aspens, and hybrids thereof, hereafter referred to as hybrid poplars), *Salix* (willows), *Pinus* (pines), and *Eucalyptus* (eucalypts) [5, 6]. Among these options, intensively grown hybrid poplars have gained substantial attention in the North Central region. Hybrid poplars are one of the most sustainable sources of biomass, and decades of research and development have resulted in production management systems that support conservation of soil and water, recycling of soil nutrients, and preservation of genetic diversity [7]. 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.

Biomass yields are largely determined by (1) the combination of genetically controlled, physiological processes, which regulate tree growth, and (2) the quality of the site, which is in turn influenced by climatological and soil factors. 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 [8–10]. More specifically, 3-PG uses solar radiation and temperature data along with species-specific photosynthetic parameters to establish maximum potential productivity, from which actual productivity is estimated based on limiting factors such as site fertility and water availability (as influenced by precipitation, soil water holding capacity, water table access, etc.) and allocated among tree components (stems, foliage, and roots) based on allometric relationships. Thus, productivity is estimated based on the site-specific availability of key resources and the species-specific physiological processes, which govern the conversion of these resources into biomass.

While 3-PG has been used both to model growth and to estimate site productivity for eucalypt and pine species [11], and the model has been tested in Canada for hybrid poplar [12] and willow [13], similar reports for hybrid poplars in the USA are lacking. Therefore, given the heightened interest in using these purpose-grown trees for energy, fiber, and environmental benefits, our objectives were to 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. This type of map-based approach is already being utilized with statistical models for poplars and willows in the UK [14] and is important for providing industry leaders, policymakers, and resource managers with much-needed information in areas where limited yield data are currently available.

Parameter Value Assignment

The spreadsheet-based version of 3-PG (known as 3-PGpjs) was obtained from the Commonwealth Scientific and Industrial Research Organization headquartered in Canberra, Australia. Users can enter species-specific values for up to 60 parameters that describe tree physiology and allometric growth relationships. In this study, we estimated the majority of these parameter values from previously published research on hybrid poplars, assumed values based on expert knowledge or best-fit of the model for a limited selection of the parameters, and used default 3-PG values for the remaining parameters (Table 1).

Literature-Derived Values

Previous research has explored the sensitivity (i.e., change in model output relative to change in model parameter) for the 3-PG model [15], and based on those results the parameters have been placed in sensitivity classes (low, medium, or high) to aid in adapting the model to new species [10]. A review of previously published poplar research was conducted to determine values for the model 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 (*Populus deltoides* × *Populus nigra* hybrids DN17, DN34, and DN182) 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; for more information on these procedures, see Appendix.

Assumed Values

For several parameters, values were assumed based on the knowledge and experience of the authors and their collaborators. 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% mortality rate concentrated early in the rotation; this is considered typical for hybrid 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. [16], in which they showed that the average SLA for *P. tremuloides* occurred at heights of approximately 7.5–10 m; similar heights are frequently achieved around age 5 for the hybrid 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 "Model Calibration."

Default Values

For the remaining parameters, default values were used. Several are conversion factors, and all are identified by Sands [10] as parameters which may be assigned generic values.

Table 1 Parameter values derived from hybrid poplar literature, assumed from expert knowledge or best-fit, or based on default 3-PG values

Parameter	3-PG name	Sensitivity class	Hybrid poplar value	Sources
Literature-derived values				
Foliage:stem partitioning ratio at DBH=2 cm	p_{FS2}	H	0.71	[41][a]
Foliage:stem partitioning ratio at DBH=20 cm	p_{FS20}	H	0.12	[41][a]
Constant in the stem mass vs DBH relationship	a_S	M	0.081	[40][b]
Power in the stem mass vs DBH relationship	n_S	H	2.46	[40]
Maximum fraction of NPP to roots	p_{Rx}	M	0.7	[42]
Minimum fraction of NPP to roots	p_{Rn}	M	0.17	[43] [b]
Mature litterfall rate per month	$\mathrm{gammaF_x}$	H	0.10	[44] [b]
Litterfall rate per month at t=0	$\mathrm{gammaF_0}$	L	0.083	[45] [b]
Average monthly root turnover rate	gammaR	L	0.02	[46] [b]
Minimum temperature (°C) for growth	T_{min}	L	10	[47]
Optimum temperature (°C) for growth	T_{opt}	M	30	[48]
Maximum temperature (°C) for growth	T_{max}	L	48	[49]
Value of "m" when fertility rating (FR)=0	m_0	L	1	[42][b]
Value of 'fNutr' when FR=0	f_{N0}	M	0.26	[38][a]
Power of (1-FR) in "f_{Nutr}"	f_{Nn}	L	1	[38][a]
Max. stem mass (kg tree^{-1}) at 1,000 trees/ha	$w_{Sx1,000}$	L	500	[39, 40][a]
Power in self-thinning rule	thinPower	L	−1.45	[39, 40][a]
Specific leaf area (m^{2}kg^{-1}) at age 0	$\mathrm{SLA_0}$	L	19	[48]
Specific leaf area (m^{2}kg^{-1}) for mature leaves	$\mathrm{SLA_1}$	H	10	[40][b]
Extinction coefficient for absorption of PAR by canopy	k	M	0.779	[50]
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	M	0.24	[51]
LAI for maximum rainfall interception	LAImaxIntcptn	L	7.3	[51]
Maximum canopy quantum efficiency (mol C mol PAR^{-1})	Alpha	H	0.08	[52]
Ratio NPP/GPP	Y	H	0.43	[53]
Maximum canopy conductance (ms^{-1})	MaxCond	H	0.02	[54]
LAI for maximum canopy conductance	LAIgcx	L	2.6	[54]
Stomatal response to VPD (1 mbar^{-1})	CoeffCond	L	0.05	[55][b]
Canopy boundary layer conductance (ms^{-1})	BLcond	L	0.05	[56][b]
Branch and bark fraction at age 0	$\mathrm{frac_{BB0}}$	L	0.64	[42]
Branch and bark fraction for mature stands	$\mathrm{frac_{BB1}}$	L	0.24	[44][b]
Age (years) at which fracBB=0.5(fracBB0+fracBB1)	$\mathrm{t_{BB}}$	L	3	[42]
Basic density (tm^{-3}) for young trees	rhoMin	H	0.39	[57]
Basic density (tm^{-3}) for older trees	rhoMax	H	0.35	[57]
Age (years) at which basic density=0.5(rhoMin+rhoMax)	tRho	M	2	[57]
Constant in the stem height relationship	a_H	L	0.036	[39][a]
Power of DBH in the stem height relationship	$\mathrm{n_{HB}}$	L	1.335	[39][a]
Power of stocking in the stem height relationship	n_{HN}	L	0.354	[39][a]
Constant in the stem volume relationship	$\mathrm{a_V}$	L	0.0072	[40][a]
Power of DBH in the stem volume relationship	n_{VB}	L	1.96	[40][a]
Power of stocking in the stem volume relationship	n_{VN}	L	−0.30	[40][a]
Assumed Values				
Age in months at which litterfall rate has median value	t_{gammaF}	L	18	
Mortality rate (%year^{-1}) for large t	$\mathrm{gammaN_x}$	L	0	
Seedling mortality rate (%year^{-1}) at t=0	$\mathrm{gammaN_0}$	L	3.5	
Age (years) at which mortality rate has median value	$\mathrm{t_{gammaN}}$	L	1	
Shape of mortality response	$\mathrm{n_{gammaN}}$	L	1	

Table 1 (continued)

Parameter	3-PG name	Sensitivity class	Hybrid poplar value	Sources
Age (years) at which specific leaf area=0.5(SLA0+SLA1)	t_{SLA}	L	5	
Age (years) at canopy cover	fullCanAge	M	5[c]	
Default values				
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 (years) 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 tree foliage biomass lost per dead tree	m_F	L	0	
Fraction mean tree root biomass lost per dead tree	m_R	L	0.2	
Fraction mean tree stem biomass lost per dead tree	m_S	L	0.2	
Intercept of net vs solar radiation relationship ($W m^{-2}$)	Q_a	H	−90[d]	
Slope of net vs solar radiation relationship	Q_b	H	0.8[d]	
Molecular weight of dry matter (dry $g mol^{-1}$)	gDM_mol	H	24[d]	
Conversion of solar radiation to PAR ($mol MJ^{-1}$)	molPAR_MJ	H	2.3[d]	

Parameter descriptions, 3-PG names, sensitivity classes, and default values are from Sands [10]

[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

[c] Parameter value assigned by iterative manipulation to produce best-fit model

[d] Conversion factors; values assumed to be constant

Model Calibration

Regional calibration of 3-PG requires (at minimum) growth data from multiple sites, along with monthly climate data 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 [10]. The following sections describe the biomass plantation data, monthly climate data, and soils data used in this study (summarized in Table 2), as well as the procedures used for manipulating our unknown parameter (fullCanAge) and the fertility rating (FR) growth modifier.

Aboveground Biomass Productivity Data

Netzer et al. [17] reported hybrid poplar biomass productivity for a number of sites planted on former agricultural fields in the North Central region in 1987 and 1988. In that study, aboveground dry biomass productivity (averaged across 25-tree blocks of each of the three hybrids DN17, DN34, and DN182) was reported for 12 plantations in Wisconsin, Minnesota, and the eastern Dakotas planted at 2.4×2.4-m spacing and measured at multiple ages (ranging from 3 to 11 years). This dataset (81 total data points) was used for calibration (56 data points from 8 plantations) and validation (25 data points from 4 plantations) of 3-PG for total stem biomass (output variable W_S; $Mg ha^{-1}$). Clone-specific data were also reported for ages 8–11 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.

Climate and Soils Data

Climate data (total precipitation, mean daily maximum temperature, mean daily minimum temperature, and mean daily solar radiation) were retrieved from databases [18, 19] for each month of each year that the plantations were grown, using the weather stations nearest each site. Relevant soils data (texture, maximum available soil water, and depth to water table) were determined for each site based on published soil surveys [20].

Because available water in the top meter of soil is typically considered accessible to plants [21], maximum available soil water (ASW_{max}) was set equal to that reported in the soil survey for the top 100 cm. We developed the following equation to estimate minimum available soil

Table 2 Plantations from Netzer et al. [17] used for calibration and validation of 3-PG for hybrid poplars

Dataset	Site	Location	Y	N	L (ºN)	T/S ID[a]	P ID[b]	T_{max}[c] (°C)	T_{min}[c] (°C)	P (mm yea^{-1})	S[d] (MJ m^{-2} day^{-1})	Soil texture[e]	D_w (cm)[e]	ASW_{max} (mm)[e]	ASW_{min} (mm)[f]
Calibration	ASH87	Ashland WI	1987	6	46.63	14,913; 727,445	475,286	17.7	6.1	807	13.0	Silt loam	30	131	92
	ASH88	Ashland WI	1988	5	46.63	14,913; 727,445	475,286	17.9	6.4	815	13.0	Silt loam	30	131	92
	FRM88	Fairmont MN	1988	6	43.68	14,925; 726,586	212,698	20.8	9.7	837	13.8	Clay loam	>100	182	0
	GRF87	Granite Falls MN	1987	7	44.80	14,922; 726,559	215,563	20.8	9.8	662	14.0	Loam	75	164	41
	GRF88	Granite Falls MN	1988	6	44.80	14,922; 726,559	215,563	20.7	9.8	670	13.9	Loam	>100	192	0
	MIL87	Milaca MN	1987	9	45.77	14,926; 727,475	215,392	20.4	7.7	660	13.2	Silty clay loam	0	196	196
	MON87	Mondovi WI	1987	9	44.87	14,991; 726,435	475,563	21.3	9.1	839	12.9	Silt loam	>100	215	0
	MON88	Mondovi WI	1988	8	44.87	14,991; 726,435	475,563	21.4	9.2	843	13.0	Silt loam	>100	211	0
Validation	CLO88	Cloquet MN	1988	7	46.83	14,913; 727,450	211,630	17.5	6.9	826	12.9	Loam	>100	163	0
	FAR87	Fargo ND	1987	6	46.90	14,914; 727,530	322,859	21.2	8.6	496	13.3	Silty clay	23	158	122
	SXF87	Sioux Falls SD	1987	6	43.57	14,944; 726,510	397,667	22.5	9.8	605	14.0	Silty clay loam	>100	190	0
	SXF88	Sioux Falls SD	1988	6	43.57	14,944; 726,510	397,667	22.3	9.8	634	13.9	Silty clay loam	>100	181	0

Y year planted, *N* number of years of data, *L* latitude, *T/S ID* temperature and solar station identification numbers, *P ID* precipitation station identification number, T_{max} mean growing season maximum temperature, T_{min} minimum temperature, *P* mean annual precipitation, *S* mean daily solar radiation, D_w depth to water table, ASW_{max} maximum available soil water, ASW_{min} minimum available soil water

[a] Temperature and solar radiation data were obtained from the National Renewable Energy Lab (NREL) National Solar Radiation Database [18]. The time period (1987–1998) for the plantations 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 [19]

[c] Calculated by averaging monthly temperatures for April through October

[d] Calculated by averaging solar radiation values for all months of the year

[e] Soil data were obtained from the Natural Resource Conservation Service (NRCS) Web Soil Survey [20]

[f] Estimated using the Eq. 1 (see text)

water (ASW_{min}) as a proportion of ASW_{max} based on minimum annual depth to water table (D_w):

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

where any D_w>100 cm is assigned a value of 100.

We evaluated other cutoffs for water table depth (50, 150, and 200 cm); however, their use did not improve the performance of the model relative to using a depth of 100 cm (results not shown). Because the plantations were established during what Netzer et al. [17] 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 3).

Optimizing Model Fit

For fitting the model to the calibration sites, the FR growth modifier and full canopy age (fullCanAge) parameter were systematically manipulated to determine the best-fit values for the calibration dataset; 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 upon potential growth to account for differences in 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 (1) it is possible all the sites have FR≈1, based on the agricultural history of the sites resulting in high levels of residual nutrients (particularly at depths below the rooting zone of annual crops but still accessible to tree roots), and (2) if FR≠1 for all sites, 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 fullCanAge result in higher estimates of biomass, whereas decreasing values of FR result in lower estimates of biomass; thus, in order to maintain predicted values at levels similar to actual values, a decrease in fullCanAge must be met with a decrease in FR. Based on the above assumptions, it is possible to (1) 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, (2) 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 calibration sites, (3) 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 (4) 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. RMSE reflects the variability between actual and predicted values and was calculated as the square root of the mean squared differences between actual and predicted values.

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- or underprediction) be avoided]. The resulting combinations of fullCanAge and FR, along with fit statistics, are shown in Table 4. Because the combination of FR=1 and fullCanAge=5 produced the best fit (R^2=0.88, RMSE=8.8 Mgha^{-1}), these values were used for the remainder of the study. However, it should be noted that the fit statistics were relatively similar for FR=0.95 with fullCanAge=4, and FR=0.90 with fullCanAge=3, and therefore, these combinations would likely give similar results. Also of note is that the ranges of values for fullCanAge and FR described above are consistent with previous research; Strong and Hansen [22] suggest that hybrid poplars utilized for 10-year rotations will reach canopy closure around age 4, and previous 3-PG studies with eucalypts demonstrated FR values ranging from 0.70 to 0.95 [23] and 0.60 to 1.00 [24] across study sites.

Table 3 Classification scheme for assigning soils to the groups found in 3-PG [8]

3-PG soil groups	Soil textures	Approximate composition
Clay (C)	Clay, sandy clay, silty clay	>40 % clay
Clay loam (CL)	Clay loam, sandy clay loam, silty clay loam	20–40 % clay
Sandy loam (SL)	Sandy loam, loam, silt loam, silt	<20 % clay, <80 % sand
Sand (S)	Sand, loamy sand	<20 % clay, >80 % sand

Table 4 Evaluated and best-fit (italic) 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 (Mgha^{-1})
3	1.00	0.90	−3.82	0.875	12.86
3	0.95	0.94	−3.67	0.874	11.04
3	*0.90*	*0.99*	*−3.49*	*0.873*	*9.69*
4	1.00	0.92	0.36	0.875	9.77
4	*0.95*	*0.96*	*0.46*	*0.875*	*8.94*
5	*1.00*	*0.95*	*3.60*	*0.880*	*8.77*

Model Validation

The calibrated model was used to predict total aboveground biomass productivity of the four plantations from Netzer et al. [17] assigned to the validation dataset (described in the preceding section). 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 (R^2, RMSE, and mean bias) for the validation dataset, as determined by linear regression of actual biomass on predicted biomass, is shown in Fig. 1. Mean bias reflects the tendency of the model to overpredict (bias>0) or underpredict (bias<0) actual biomass and was calculated by summing the differences between actual and predicted annual biomass and then dividing by the number of observations.

In addition to the overall fit of the model, the fit of the model for the individual sites was also evaluated. Linear regression coefficients (slope and intercept) for actual versus predicted biomass were determined for the sites via analysis of covariance using PROC GLM in SAS (SAS Institute Inc., Cary, NC, USA), with actual biomass as the dependent variable, site as the independent variable, and predicted biomass as the covariate. The values ranged from 0.70 to 1.18 for the slopes, and −13.2 to 17.6 for the intercepts (Fig. 2). To examine the relationship of individual sites relative to the overall model, a surrogate site (MON87) was selected to represent the overall model (based on similarity of slope and intercept), and statistical contrasts were then used 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), and MON88 (P=0.0056).

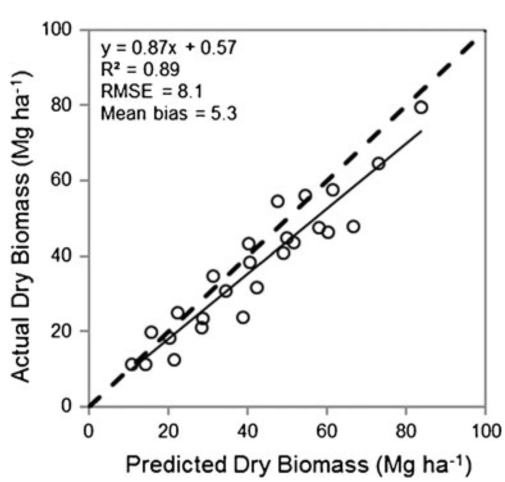

Fig. 1 Fit of the calibrated model to the data used for validation for total aboveground biomass (Mgha^{-1}). The *dashed line* represents 1:1 ratio of actual versus predicted dry biomass

Finally, the ability of the model to effectively identify high versus low productivity sites is of interest for siting bioenergy facilities and the hybrid poplar plantations which would supply them. Actual and predicted biomass growth over time is shown for plantations established in 1987 (Fig. 3) and 1988 (Fig. 4).

Sensitivity Analysis

The sensitivity of the model, as calibrated for hybrid poplars in the region, was evaluated by separately manipulating fullCanAge and FR. These parameters were selected due to the uncertainty of their true values; the parameters were estimated via model optimization during model calibration. The sensitivity of the model was evaluated in terms of mean annual biomass productivity (Mgha^{-1}year^{-1}) rather than overall productivity (Mgha^{-1}), so that these measures of variability would be consistent with the units to be used for mapping productivity (described in the following section). The model was run with fullCanAge set at 3, 4, 5, 6, and 7 years (with FR=1) to determine the mean bias and RMSE for the calibration sites, the validation sites, and all sites (calibration+validation). Similarly, the model was also run with FR set at 1.00, 0.95, 0.90, 0.85, and 0.80 (with fullCanAge=5) for these datasets. In addition, individual sites were evaluated for RMSE to determine their best-fit values for fullCanAge and FR.

Biomass productivity was sensitive to manipulation of the fullCanAge parameter (Fig. 5). A change of 2 years in either direction from age 5 produced a mean bias of −0.4 to 2.0 Mgha^{-1}year^{-1} for the validation sites and −1.1 to 1.6 Mgha^{-1}year^{-1} across all sites (Fig. 5a). Decreasing FR from 1.00 to 0.80 produced a mean bias of −0.3 Mgha^{-1} year^{-1} for the validation sites and −0.9 Mgha−$^{-1}$year^{-1} across all sites (Fig. 5b).The calibration sites and the overall dataset achieved best-fit at fullCanAge=5 and at FR=1, while the validation sites achieved best-fit at fullCanAge= 6 and at FR=0.85. Similarly, the best-fit values of fullCanAge and FR varied among individual sites (Fig. 6). Most of the individual sites achieved best-fit with values of 4–6 for fullCanAge; however, one site (MON88) achieved best-fit at fullCanAge=3, while two sites (ASH87 and SXF87) achieved best-fit at fullCanAge=7. The majority of sites achieved best-fit at FR=1; however, one site (FAR87) achieved best-fit at FR=0.90 and four others (ASH87, FRM88, SXF87, and SXF88) achieved best-fit at FR=0.80.

Mapping Aboveground Biomass Productivity

Once calibrated and validated for the region, 3-PG was used to model productivity across Minnesota and Wisconsin

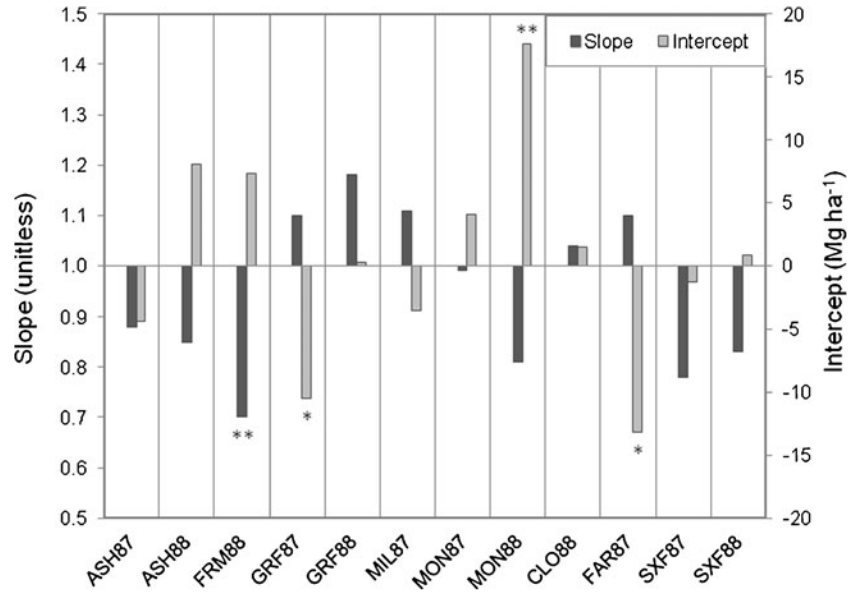

Fig. 2 Results of linear regression for predicted biomass versus actual biomass by site. Significant differences at $*P<0.05$, $**P<0.01$, and $***P<0.001$, from contrasts of the surrogate site for the overall model (MON87) vs all other sites. Calibration sites are ASH87, ASH88, FRM88, GRF87, GRF88, MIL87, MON87, and MON88; validation sites are CLO88, FAR87, SXF87, and SXF88

within a geographic information system (GIS; ArcGIS, ESRI, Redlands, CA, USA). Temperature, precipitation, and solar radiation climate data (32-km resolution) were retrieved from the North American Regional Reanalysis (NARR) [25] through the NOAA National Operational Model Archive and Distribution System (NOMADS) [26, 27]. The NARR climate data (Lambert conformal grid format, [25]) were attributed to an ArcGIS 32-km base grid using geo-referenced latitude and longitude coordinates. The data consisted of 8 data points per month (each one representing a 3-h period of the day), for each month over a 10-year period (1998–2008), giving a total of 960 observations per climate variable; maps of the study area produced from these climate data have been recently published [28].

To determine whether to use 2-m temperature or surface temperature from the NARR data, both were compared to weather station data at three locations (Fairmont, Granite Falls, and Milaca, MN, USA) over the period 1987–1998. The results showed that maximum temperature is closely matched by the 2-m data, while minimum temperature is closely matched by the surface data; as such, this combination of temperature data was used for the remainder of the mapping process. Average monthly values of maximum and minimum temperatures were determined by averaging the maximum and minimum 3-h 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-h 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-

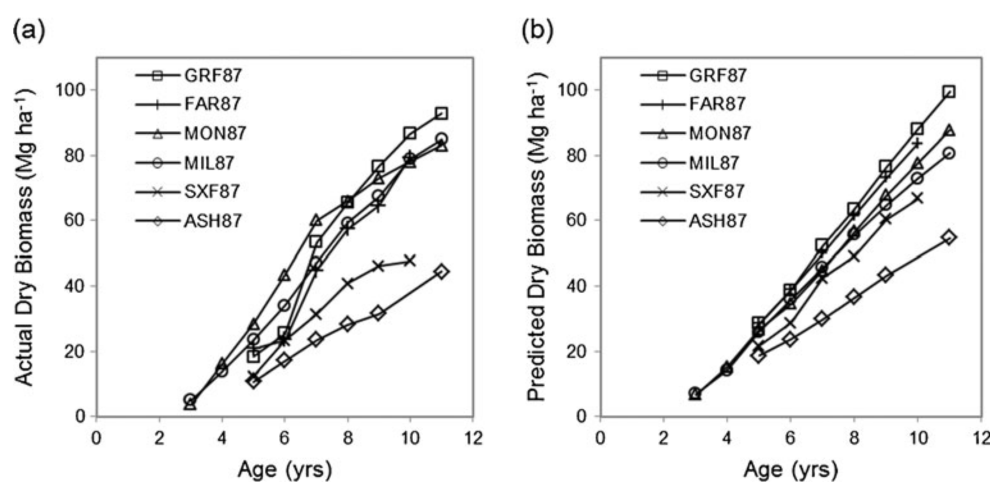

Fig. 3 Actual (**a**) and predicted (**b**) biomass productivity for hybrid poplar plantations established in 1987. Calibration sites include ASH87 (*diamond*), GRF87 (*square*), MIL87 (*circle*), and MON87 (*triangle*); validation sites include FAR87 (*plus symbol*) and SXF87 (*ex symbol*)

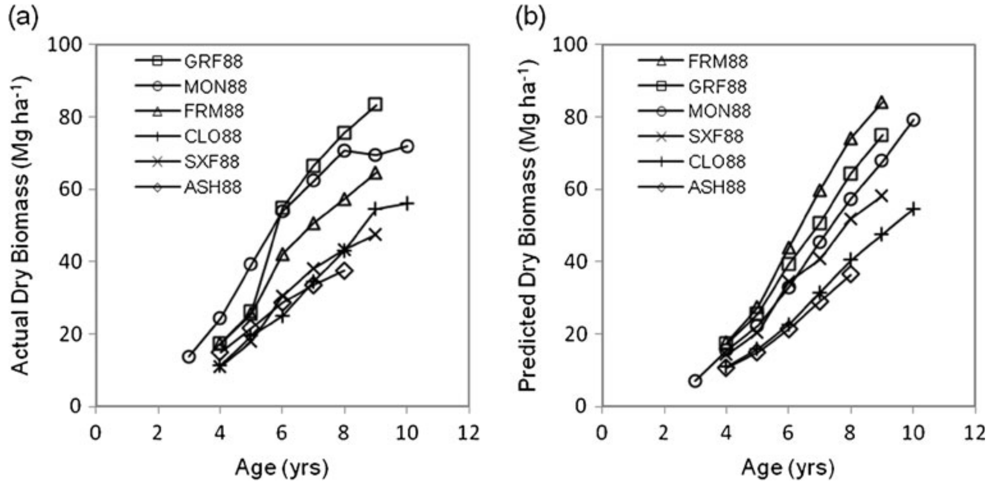

Fig. 4 Actual (**a**) and predicted (**b**) biomass productivity for hybrid poplar plantations established in 1988. Calibration sites include ASH88 (*diamond*), FRM88 (*triangle*), GRF88 (*square*), and MON88 (*circle*); validation sites include CLO88 (*plus symbol*) and SXF88 (*ex symbol*)

h 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 hday^{-1}.

Soils data were retrieved through the State Soil Geographic (STATSGO2) database from the Natural Resource Conservation Service [29]. 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

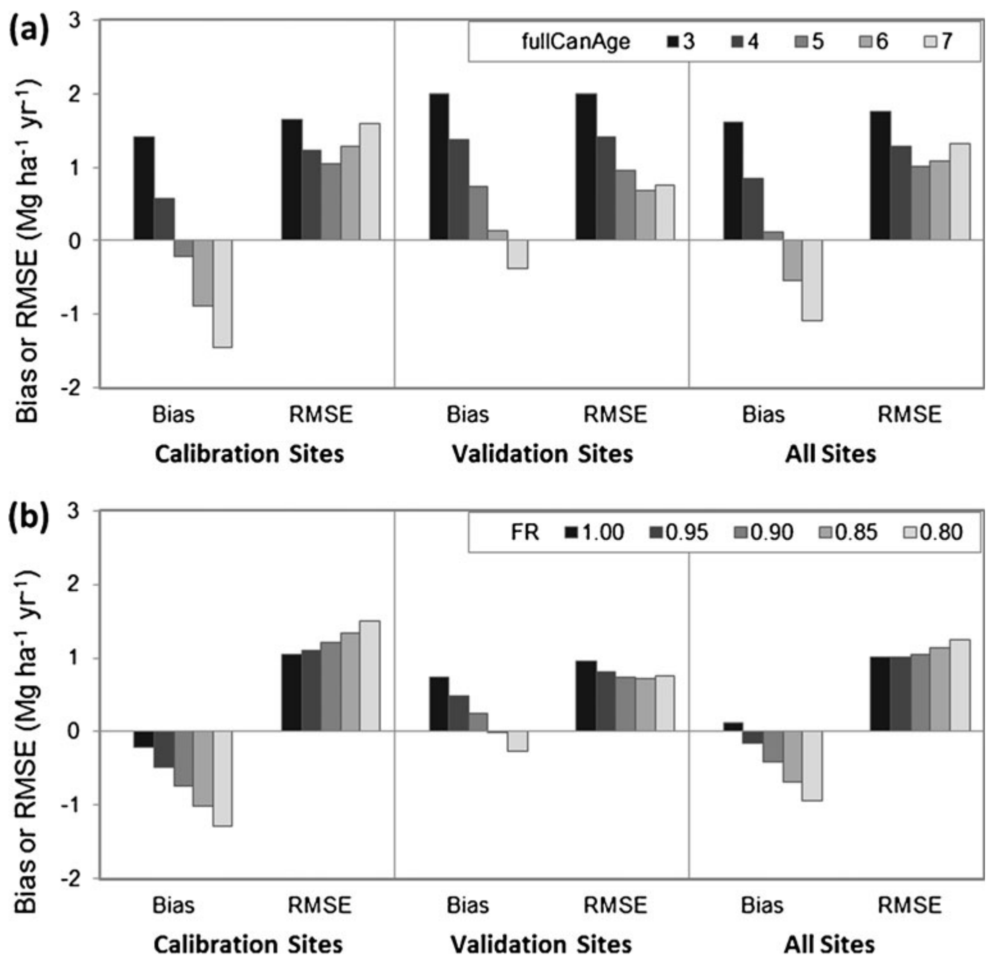

Fig. 5 Sensitivity (mean bias and RMSE; Mg$ha^{-1}year^{-1}$) of the model for calibration, validation, and all (calibration+validation) sites for various levels of (**a**) the full canopy age (fullCanAge) parameter (at FR=1), and (**b**) the fertility rating (FR) growth modifier (at fullCanAge=5)

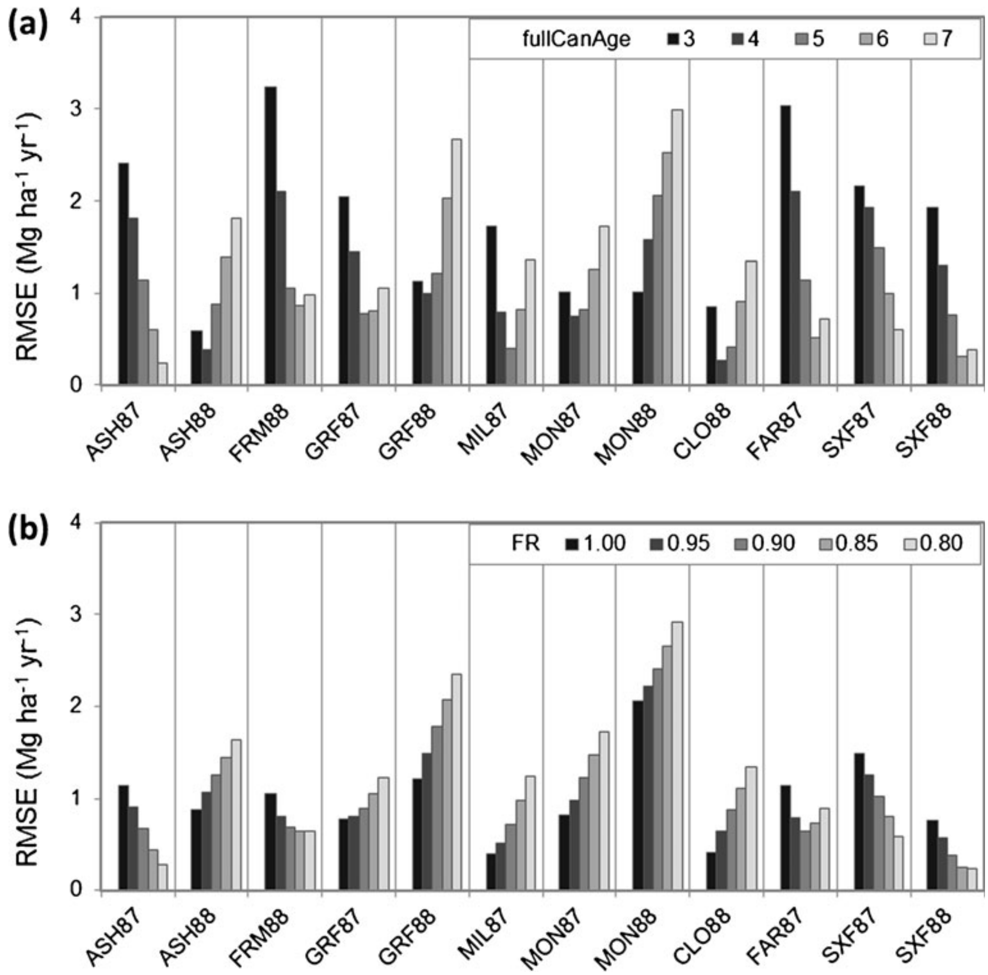

Fig. 6 Model fit (RMSE; Mgha^{-1}year^{-1}) by site for various levels of (**a**) the full canopy age (fullCanAge) parameter, and (**b**) the fertility rating (FR) growth modifier. Calibration sites are ASH87, ASH88, FRM88, GRF87, GRF88, MIL87, MON87, and MON88; validation sites are CLO88, FAR87, SXF87, and SXF88

the "component" table). The soil map units were then assigned to soil texture groups according to Table 3.

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. Mean annual biomass productivity (Mgha^{-1}year^{-1}) at age 10 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. Mean annual biomass productivity was used for mapping because these units are commonly reported in the literature and to facilitate comparison with annual crops; it was calculated by dividing the total aboveground dry biomass by age. The age 10 was selected because it is within the range of rotation lengths (7–10 years) suggested for the region by Netzer et al. [17] and because it allows for simple conversion to total biomass (Mgha^{-1}). The resulting map of predicted biomass for Minnesota and Wisconsin is shown in Fig. 7. Annual biomass productivity at age 10 ranged from 4.4 to 13.0 Mgha^{-1} year^{-1} across the states, with the highest productivity mainly concentrated in the area stretching from south-central Minnesota across southern Wisconsin.

Discussion

As parameterized and calibrated in this study, 3-PG appears well suited for modeling hybrid poplar aboveground biomass productivity in Minnesota and Wisconsin. Linear regression of actual versus predicted total aboveground biomass for the validation dataset demonstrated a strong fit (R^2=0.89, RMSE=8.1 Mgha^{-1}, mean bias=5.3 Mgha^{-1} or 14.3 % of mean observed biomass; see Fig. 1). These results are similar to other studies with 3-PG, where R^2 values of 0.63–0.99 [11, 30–32] and mean bias of 4 to 22 % [11, 30] for aboveground biomass have been reported for plantations of various species. Individually, few sites deviated significantly from the overall model with regard to slope and intercept for actual versus predicted biomass (see Fig. 2), and the model was able to separate higher productivity sites from lower productivity sites (see Figs. 3 and 4).

When used to map productivity across Minnesota and Wisconsin (see Fig. 7), mean annual biomass predictions and their spatial trends were consistent with previous research. Specifically, the range of biomass estimates (4.4–13.0 Mg ha^{-1}year^{-1}) is consistent with that observed for DN34 (4.80–9.01 Mgha^{-1}year^{-1}; ages 7–10 years) at sites in

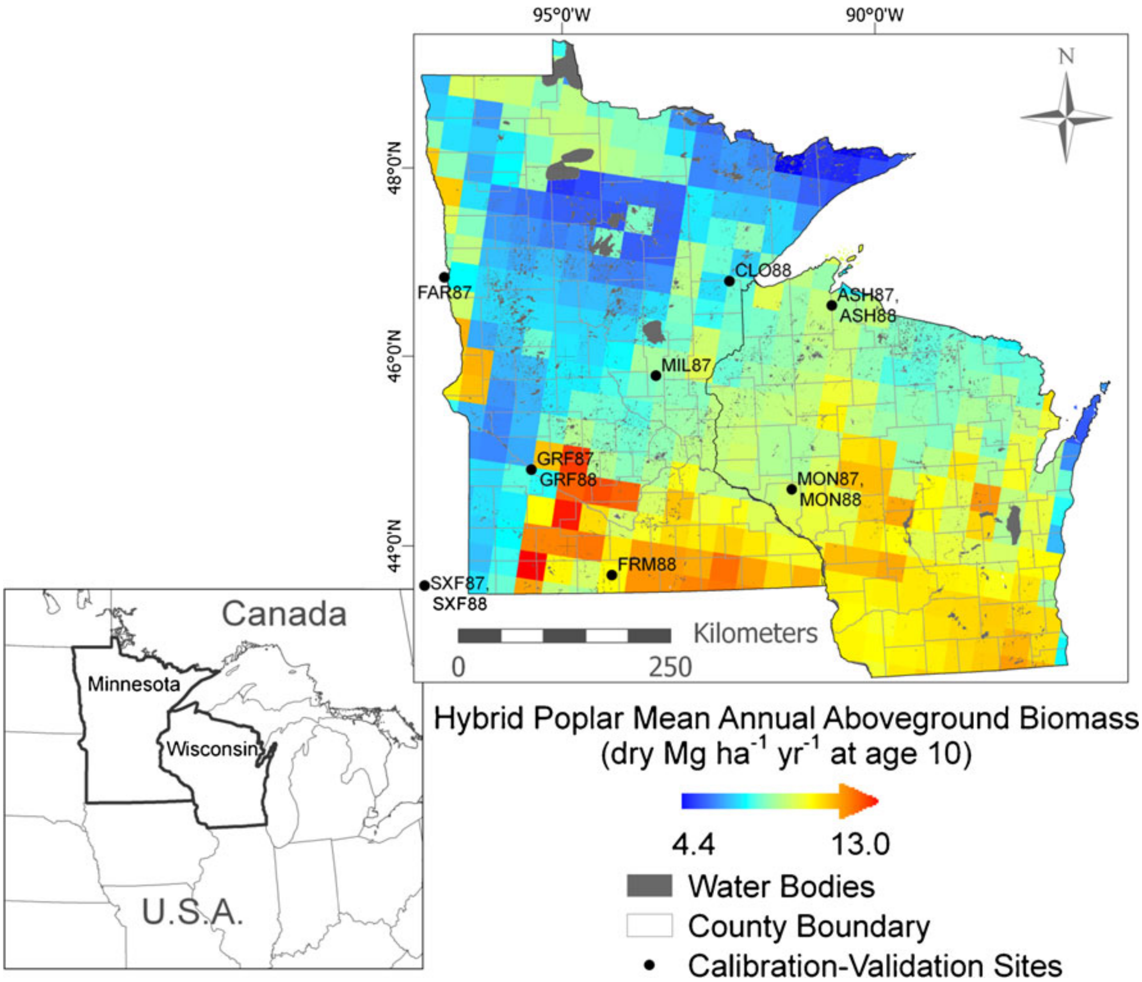

Fig. 7 Map of predicted mean annual aboveground biomass productivity (dry $Mgha^{-1}year^{-1}$) for hybrid poplars on a 10-year rotation in Minnesota and Wisconsin. Calibration sites are ASH87, ASH88, FRM88, GRF87, GRF88, MIL87, MON87, and MON88; validation sites are CLO88, FAR87, SXF87, and SXF88

Minnesota and Wisconsin reported by Zalesny et al. [4] and the overall spatial trend mirrors that of corn grain productivity for the region as mapped by Prince et al. [33]. Interestingly, biomass productivity is predicted to be highest near the boundary between high and low productivity in southern Minnesota; this pocket of high-productivity is also apparent on the aforementioned corn grain productivity map and may stem from shallower water tables [20] along with relatively high solar radiation and temperature [18]. The RMSE values associated with mean annual productivity (see Fig. 5) suggest that, as currently calibrated, actual productivity will typically vary from mapped values by ±1 $Mgha^{-1}year^{-1}$.

Table 5 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
MON87	0.95	4
MON88	1.00	3
CLO88	0.95	4
FAR87	0.90	5
SXF87	0.85	6
SXF88	0.90	5

The sensitivity analysis suggests that biomass productivity is more sensitive to fullCanAge than to FR within the range of values tested in this study (see Fig. 5), albeit with a relatively smaller range of potential FR values being tested compared to fullCanAge. A decrease in fullCanAge of 2 years resulted in a mean bias of 1.6 $Mgha^{-1}year^{-1}$ across the entire dataset, while a decrease in FR of 0.20 resulted in a mean bias of −0.9 $Mgha^{-1}year^{-1}$. The validation dataset achieved best-fit at fullCanAge=6 and at FR=0.85, which indicates the use of fullCanAge=5 and FR=1 may overestimate actual productivity; however, to the extent that FR may be raised with fertilization, use of the latter values may be considered reflective of potential productivity. Differences among individual sites within the calibration and validation datasets are also evident (see Fig. 6). The apparent separation of sites by best-fit values of FR may be related to disease: all four sites having best-fit FR=0.80 (ASH87, FRM87, SXF87, and SXF88) were rated by Netzer et al. [17] as being among the most severely affected by stem canker. Similarly, these four sites also had higher best-fit values of fullCanAge (6–7 years) than the other sites (3–5 years) with the exception of FAR87 (6 years). Finally, the plantations established in 1987 generally achieved best-fit at higher values of fullCanAge (4–7 years) than those established in 1988 (3–6 years). This may be due to better establishment conditions (relating to extreme weather events, site preparation, and/or weed control) for the 1988 plantations.

These possible disease and establishment effects suggest that a more complete accounting of damaging agents (i.e., insects, weed competition, and extreme weather events) would likely produce more accurate biomass productivity estimates. Likewise, more specific knowledge of physiological parameters (i.e., clone-specific values rather than those for parent species or related clones) should be the subject of additional research to improve model performance. 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 may range from 0.85 to 1, with fullCanAge ranging from 3 to 6 years and negatively correlated with FR (Table 5). These site-specific estimates of FR and fullCanAge improve the overall model fit (R^2=0.95, RMSE=5.4 Mgha^{-1}) but require prior knowledge of yields, and therefore, we did not attempt to use or validate these site-specific values in the present study. To this end, methods for reliably measuring FR and predicting fullCanAge for individual sites without prior knowledge of yields should also be further investigated.

Even though coefficients for other output variables (i.e., DBH, height, volume, and self-thinning) were obtained from the literature, the model was only calibrated and validated for aboveground biomass in this study. Additional work should be done to validate model outputs for these other stand variables. In addition, it is important to reiterate that the model was only calibrated and validated for the group of clones (DN17, DN34, and DN182) reported in Netzer et al. [17]. As has been observed for *Eucalyptus* [34], different 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 recalibrated for these clones (or groups of clones), especially when they are not closely related to the ones considered here. While many of the physiological parameters and allometric relationships likely apply equally well in other regions for these specific clones, other values (or ranges of values) are likely to occur for variables such as FR. Likewise, the most suitable cutoff for depth to water table in the ASW_{min} equation may also vary by region.

Although the results of this study are promising, it should not be considered the final word in 3-PG calibration for hybrid poplars in the region. Rather, it is intended as a first approximation, which can and should be improved based on additional research, particularly with regard to determining clone-specific values for physiological parameters and site-specific values for FR. In addition, due to the coarse scale of the biomass productivity map, it should not be used for siting hybrid 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, nonbiological factors such as land ownership and current land use [35–37] place constraints on poplar deployment, which are not considered here. Additional work has been conducted to evaluate the potential of using 3-PG to predict and map biomass yields at finer scales, with consideration for such constraints [28].

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Appendix

Fertility Rating Equation

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

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

which can be rearranged as:

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

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_{f_N} 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.

Previously published data for stem volume and leaf N concentration from a fertility study of four *Populus trichocarpa*×*P. deltoides* clones [38] 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_{f_N} in the rearranged equation above, using linear regression in SAS (PROC REG). The resulting model (R^2=0.89) estimates the values of the parameters as: f_{N0}=0.26; n_{f_N}=1.

Stem Height Relationship

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

$$H = a_H \times B^{n_{HB}} \times N^{n_{HN}} \tag{4}$$

or when log-transformed

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

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.

Previously published data (mean heights in meters, mean DBH in centimeters, and trees per hectare derived from tree spacing) from a previous study with *P. trichocarpa*×*P. deltoides* and *P. trichocarpa*×*P. nigra* clones [39] 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:

$$V_s = a_v \times B^{n_{VB}} \times N^{n_{VN}} \tag{6}$$

or when log-transformed

$$\ln V_s = \ln a_v + n_{VB}(\ln B) + n_{VN}(\ln N) \tag{7}$$

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.

Previously published data (trees per hectare, DBH in centimeters, and volume estimated from mean annual mass increment×age×basic density) from a study on an array of hybrid poplars [40] 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, and a_V=0.0072.

Self-Thinning Relationship

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

$$w_{Sx} = w_{Sx1,000}\left(\frac{1,000}{N}\right)^{n_N} \tag{8}$$

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 ($w_{Sx1,000}$) and the slope of the self-thinning line (n_N).

Stand density and mean stem biomass values were derived from DeBell et al. [39] and Johannson and Karacic [40]. The former reported these two variables directly; the latter reported stand density and mean stem diameter, which was converted to mean stem biomass using an equation given in 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. The resulting values of the coefficients are estimated as: $w_{Sx1,000}$=500; n_N=−1.45.

Foliage:Stem Partitioning

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

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

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 Fortier et al. [41] 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=3.6–25.1 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).

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