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Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG)

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ARTICLE INFO

Article history:
Received 12 December 2008
Received in revised form
22 November 2009
Accepted 6 January 2010
Available online 2 February 2010

Keywords:
Farmland afforestation
Agriculturally marginal land
Walker hybrid poplar
3PG
Short-rotation crops
Stand growth model
Canadian Prairies
Populus plantations
Bioenergy
Biomass production

ABSTRACT

Establishing short-rotation tree plantations for bioenergy and fiber production on agricultural land (abandoned farmland) would provide significant environmental and economic benefits for rural communities and society as a whole. Walker hybrid poplar (*Populus deltoides* x *P. nigra*) is one of the most commonly used varieties cultivated in Saskatchewan, Canada; however, there are no existing hybrid poplar growth models in the literature. The aim of this work was to parameterize and evaluate the 3PG model (Physiological Principles in Predicting Growth) to predict Walker tree growth in the climate and soils of Saskatchewan. We used annual data from Walker poplar trials (4- to 11-yr old stands) established at three spacing levels (2.4, 3.0, and 3.7 m) at three sites located in central Saskatchewan, Hnr, BH, and ML sites. The data were split into two sets – the modeling set from the Hnr site was used to parameterize 3PG, and the testing sets from the BH and ML sites were used to evaluate Walker growth predictions made by 3PG. The bias, sum(predicted minus observed) divided by number of observations, for tree height predictions ranged from −1.76 to 1.45 m, and bias for diameter at breast height (DBH) ranged from −2.61 to 0.66 cm. Regression R-square values of 3PG-predicted versus observed height and DBH ranged from 0.75 to 0.98. Our results indicated that, once parameterized, 3PG could predict Walker hybrid poplar growth with desirable accuracy by only utilizing commonly available soils and climate data for marginal or more productive agricultural land across Saskatchewan.

1. Introduction

Establishment and utilization of short-rotation crops (SRCs) such as hybrid poplar and willow tree species for bioenergy production could substantially decrease the overall use of fossil fuels for energy and, thus, reduce CO_2 emissions into the atmosphere [1–5]. Other significant environmental benefits spurred by SRC plantation establishment include soil organic carbon (SOC) sequestration [6,7], long-term carbon (C) storage in wood products manufactured from harvested biomass, and soil erosion control [8,9]. Especially attractive is the idea of establishing SRC production systems on waste disposal sites [10] and agriculturally marginal lands [4,11], where additional financial flow from biomass production for energy will benefit rural communities.

Research showed that growing hybrid poplar and willow in SRC plantations is ecologically and environmentally sustainable [12]. Other workers indicated through financial analyses including establishment, maintenance, and harvesting costs, land-rent and net stumpage market values that the benefit-to-

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0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2010.01.012

cost ratio of SRC systems in Canada would be between 0.73 and 1.25 when managed at optimal economic rotations ranging from 18 to 24 yr [13]. Recently, a detailed manual for hybrid poplar biomass production in the Canadian Prairies including clone properties, site selection, and recommended plantation establishment practices was published to aid farmers and corporations planning to establish SRC systems [14].

Hybrid poplar growth and biomass yield could vary significantly as a function of site characteristics, physicochemical soil properties, climatic conditions, and species genotype [10,15,16]. The above-ground biomass yield of 4-yr old hybrid poplar stands in Europe (in short-rotation coppice culture) [10] and north central USA (derived from [15]) averaged between 2 and 11 $Mg\,ha^{-1}\,yr^{-1}$ with considerable differences between clones. In comparison, growth and yield data reported in western Canada showed that 4-yr old Walker hybrid poplar stands from five locations in Saskatchewan averaged from 0.17 to 0.19 $Mg\,ha^{-1}\,yr^{-1}$ (data from the Prairie Farm Rehabilitation Administration (PFRA), Agri-Food and Agriculture Canada; published in Anderson and Luckert [13]). The PFRA has the longest measurement records for stands of different hybrid poplar clones in western Canada with stand age ranging from 4 to 25 yr. In some of the older hybrid poplar trials, PFRA yield data showed that 15 and 25 yr old Walker hybrid poplar stands averaged 3.9 (data from three 15-yr stands) and 2.0 (data from one 25-yr stand) $Mg\,ha^{-1}\,yr^{-1}$, respectively (published in Anderson and Luckert [13]), which were considerably lower than the hybrid poplar yields reported in Europe and USA. The PFRA data originated from growth trials established at various tree densities using rooted cuttings and managed for forestry applications [13], except the oldest trials. The 25-yr data were from a growth trial near Indian Head, Saskatchewan which was managed for shelterbelt applications (three-row design) with approximately 1000 trees ha^{-1} [13].

Climatic conditions and site and soil characteristics (i.e., site quality) have significant effects on the biomass yield of hybrid poplar and willow. Kopp et al. [16] showed that there was a strong positive correlation between the number of growing degree days (GDD, base 5 °C) and annual biomass production for three willow clones (correlation ranging from 0.66 to 0.93) and one hybrid poplar clone (0.95) on a site in New York state, USA. All stands were established at 0.3×0.3 m tree spacing and were harvested annually. It was suggested that if GDD were constant between growing seasons, the annual biomass production would have been a constant after year 4 of stand establishment [16]. In a study on marginal agricultural land (abandoned farmland) of contrasting soil structure and fertility (a poorer sandy loam and a relatively rich clayey soil) in southern Quebec, Labrecque and Teodorescu [11] suggested that "…once the crop is established, temperature and precipitation become the most limiting factors for willows…[in SRC systems]". In particular, the combined influence of precipitation and temperature and, hence, soil moisture availability throughout the growing season, could be crucial for maximizing biomass production. Furthermore, because of the different growth patterns of SRC tree species, e.g., very fast growth early in the season for *Salix viminalis* compared to a slower and more prolonged growth throughout the season for *S. discolor*, the effect of the distribution of precipitation during the growing season on biomass production could also vary by species [11]. In a hybrid poplar biomass production study (stand ages from 1 to 10 yr) in the Willamette Valley, Oregon, USA, biomass volume on high quality sites was approximately twice that observed on low quality sites (derived from [17]). More recently, it was shown that fertilization increased the rate that trees attained their maximum production by one year, which could imply that fertilized stands could be managed at shorter rotations [16].

Conducting research in terrestrial ecosystems is often associated with high costs and long-term periods of time before any results become available. For each aspect of SRC biomass production systems, starting from planting vigorous and disease-resistant clones, maintaining healthy forest ecosystems, and ending with biomass harvesting for bioenergy production (i.e., burning for energy and heat) or for wood product manufacturing, carefully designed studies are needed to discover the mechanisms and processes associated with sustainable tree growth, management treatments, and nutrient uptake and transportation. Tree growth simulation models, based on available empirical data or known physiological processes, or both, are often used by scientists to predict growth and yield of tree species extending many years (i.e., decades) into the future. Such model predictions could be of great advantage to landowners, regional planners and politicians. For example, tree stem volume is necessary to predict the amount of biomass that would be harvested for saw timber or pulpwood, which eventually would be used for energy or wood products.

A stand growth model, called 3PG (Physiological Principles in Predicting Growth) was developed by Landsberg and Waring [18] to assess forest productivity in Australia and New Zealand. In the past, the 3PG model has been successfully parameterized and tested across the globe in predicting forest productivity in plantations of fast-growing trees, including species of *Eucalyptus* and *Pinus* [19–22]. The 3PG model requires few input parameters and readily available soils and climate data to model the annual growth and stand development of forest stands [22]. Because of physiological differences between various tree species and their hybrids, such as the utilization efficiency of photosynthetically active radiation (PAR) for biomass synthesis and biomass allocation to different tree components, some of the input parameters for the 3PG model are determined from empirical data [22]. For example, allometric relationships for tree height, stem volume, and biomass as a function of diameter at breast height (DBH), all based on empirical data, could be used to parameterize the 3PG model for a specific tree species or a hybrid [22].

As growth and yield data for different hybrid poplar clones become available for varying soil and climatic conditions across Canada and USA, farmers and corporations planning to establish SRC systems would be able to make better management decisions. However, due to the relatively long-term nature of hybrid poplar SRC systems (i.e., multiple short rotations, each between 10 and 30 yr long [14]), growth and yield data for agricultural and marginal land are sparse. To resolve this issue and provide a good prediction for hybrid poplar growth and yield under varying growing conditions, the objectives of this paper were to (i) parameterize the 3PG model to predict growth of Walker hybrid poplar (*Populus deltoides x P. nigra*) in the climate and soils of central Saskatchewan, Canada; and (ii) evaluate the Walker-specific 3PG model performance against independent data sets for the same clone. To our knowledge, the work in this paper is the first time that the 3PG growth model has been adapted and tested for hybrid poplar grown in short-rotation production systems.

2. Methods and materials

2.1. Study sites

Walker hybrid poplar trials were established at three agricultural sites in central Saskatchewan to monitor stand development and tree growth for biomass production (Fig. 1). The original intent for these Walker trials was to study the potential use of this hybrid poplar clone as feedstock source for local pulp and paper mills and saw mills, and to research the effects of tree spacing on the type of manufactured forest products, including paper products, saw timber, and oriented-strand board (OSB). Because of the high tree densities of these Walker stands, a new and unique opportunity was recognized to study the potential use of the Walker clone for bioenergy production. The work presented in this paper is aimed at testing the 3PG growth model for predicting Walker hybrid poplar yield as cumulative biomass production for bioenergy, and no further discussion was presented about alternative forest products manufacturing.

Rooted cuttings of Walker hybrid poplar were hand-planted at three spacing levels, approximately 2.4, 3.0, and 3.7 m (or 8, 10, and 12 ft) with approximate tree densities of 1682, 1076, and 747 trees ha^{-1}, respectively (or 681, 436, and 303 tree ac^{-1}, respectively). Each spacing level was replicated three to five times with each replication being approximately 0.3 ha (0.74 ac) in size. Three replications near Meadow Lake (ML) and five replications near Henribourg (Hnr) were established in 1997, and four additional replications were established near Birch Hills (BH) in 1999 (Table 1). All sites were previously in agricultural use and were annually cropped before tree planting, with the exception of the Hnr site which was left fallow for a year. A number of physicochemical soil properties at each site were analyzed [23]. The soils at the ML site were Brunisolic Grey Luvisol, and Orthic Dark Grey Chernozem at the Hnr site, and Orthic Black Chernozem at the BH site [24] with soil textures ranging from sandy loam (ML

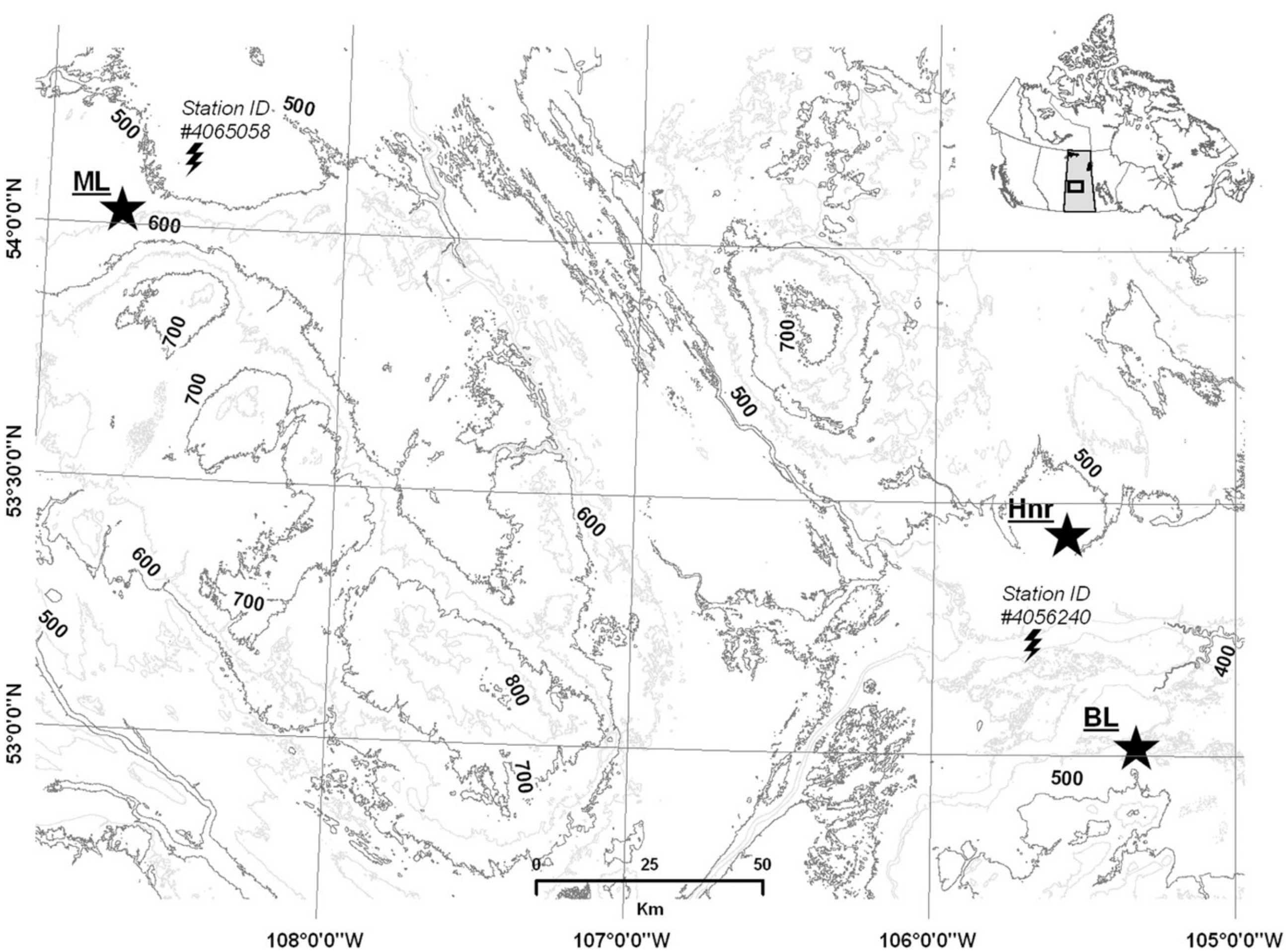

Fig. 1 – Walker hybrid poplar growth study site locations (star symbols) in central Saskatchewan, Canada; climate data for the Meadow Lake (ML) site were obtained from weather station #4065058, and data for the Henribourg (Hnr) and Birch Hills (BH) sites were from weather station #4056240.

Table 1 – Summary of the soil and climatic conditions at the three study sites planted with Walker hybrid poplar.

Site name	Planted year	Latitude/longitude	Soils[a]	Soil texture[b]	Climate[c]		
					TAP (mm)	MAT (C°)	TAF (days)
Meadow Lake (ML)	1997	54.03 N 108.75 W	Loon River Brunisolic Grey Luvisol	SL to SCL	344	1.2	216
Henribourg (Hnr)	1997	53.44 N 105.55 W	Nisbet Orthic Dark Grey Chernozem	SiL	338	1.8	205
Birch Hills (BH)	1999	53.02 N 105.32 W	Blaine Lake Orthic Black Chernozem	SiCL to CL	338	1.8	205

a Based on the Canadian system of soil classification [24].
b Soil texture abbreviations: sandy loam (SL), sandy clay loam (SCL), silt loam (SiL), silty clay loam (SiCL), clay loam (CL).
c TAP = Total annual precipitation (mm); MAT = Mean annual temperature (C°); TAF = Total annual number frost days.

site) to silt loam (Hnr site) and clay loam (BH site) (Table 1). Within the surface 25 cm of the soil, percent total soil nitrogen (N) and carbon (C) concentrations (i.e., 100 * C or N (g)/soil (g)) ranged from 0.01to 0.49% and from 0.13 to 5.76%, respectively, and followed similar trends among study sites in the decreasing order BH > Hnr > ML [23].

The Walker clone was selected for planting [25], because of its superior growth observed in shelterbelt trials, and its relative tolerance to low temperature injuries (i.e., frost damage) both early and late in the growing season [26]. Tree height (m) and DBH (cm) were measured annually between 2004 and 2007 for 36 permanently selected trees at each replication for each spacing level of each site, except for the ML site where 18 permanently selected trees were measured at each replication and spacing level (Fig. 2). Earlier measurements from 2002 were based on 9 trees at each replication for each spacing level of each site. Data from year 2000 was collected only from the replications at the ML site where all planted trees were measured. For the annual tree inventories, measurement trees were buffered with 2 (at 3.7 m spacing)–5 (at 2.4 m spacing) rows of trees to eliminate stand edge effects. Also, a 5-m buffer zone at each site was left unplanted for machinery movement.

Walker growth (tree height and DBH) was significantly different between sites for stand ages from 4 to 11 yr (Fig. 2). Consistent results of the effects of tree density on Walker

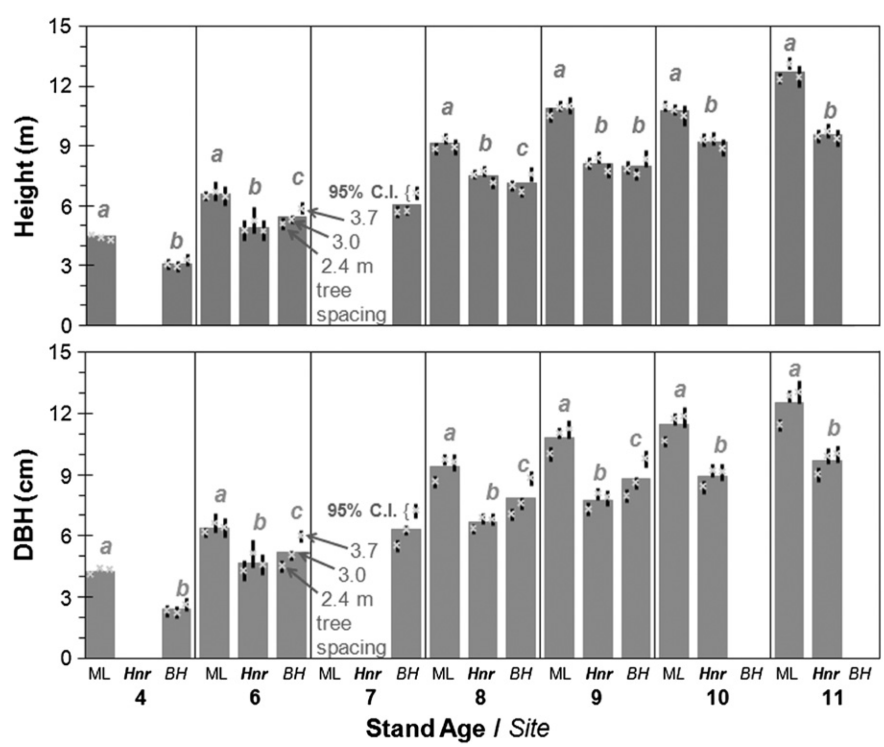

Fig. 2 – Tree height (m) and diameter at breast height (DBH, cm) data for Walker hybrid poplar stands established at three spacing levels (2.4, 3.0, and 3.7 m) on three study sites located in central Saskatchewan, Canada; Meadow Lake (ML), Henribourg (Hnr) site, and Birch Hills (BL) sites. Short vertical bars represent the 95% confidence limits of height and DBH means estimated for each spacing level at each site. Different letters (within the same age category) above graph columns indicate significant difference (at the 95% probability level) of height or DBH means between sites.

growth were not observed at any site indicating that Walker trees were not yet competing for resources (soil nutrients, water and light) up to their current age. Although other workers have observed significantly different growth of hybrid poplars at tree spacing levels below 2.0 m [27,28], our data showed the opposite at spacing levels $>=2.4$ m. Our observations that tree growth was unaffected by tree spacing (up to the current age, 11 yr) could most likely be a result of the narrow crowns and short side branching of Walker hybrid poplar trees [14]. As trees develop with age and fill the growing space above- and below-ground, between-tree competition for light, water and nutrients would intensify and changes in tree growth (i.e., rate and standing biomass) could become more discernible at varying tree spacing levels.

2.2. 3PG model parameterization

The 3PG model is based on known principles of utilizing solar radiation by plants for photosynthesis and biomass production and partitioning to tree components, foliage, stem, branches and bark, and roots. Although these fundamental principles hold true for all tree species, solar radiation utilization efficiency, tree growth characteristics (e.g., growth increment, biomass partitioning, mortality, and canopy structure) and wood properties differ among varying tree species. Such species-specific properties and features are controlled in the 3PG model by different parameters grouped into five main categories (Table 2): (i) biomass partitioning and turnover; (ii) growth modifiers; (iii) stem mortality and self-thinning; (iv) canopy structure and processes; and (v) wood and stand properties. For each variable in these categories, we assigned a value (i.e., parameterized the variable) that would best represent the growth and stand development of Walker hybrid poplar trees. We used four methods of 3PG variable parameterization. First – we used empirical observations from Walker stands established on our study sites; second – we used hybrid poplar data from the literature assuring that at least one of the hybrid parents was *P. deltoides* (eastern cottonwood); third – we used the default 3PG parameters (i.e., default for *Eucalyptus* species); and fourth – we varied the remaining parameters to fit the 3PG model output results to our Walker observations for tree height and DBH (Table 2).

We split the Walker data from our study sites into two sets. A modeling set – data from the Hnr site were used to parameterize the 3PG model; and a testing data set – data from the BH and ML sites were used to evaluate growth predictions for Walker trees made by the 3PG model. We based our selection of modeling and testing data sets on the relative soil and climatic differences between the three study sites to allow a more vigorous model testing while sufficient data were used to parameterize 3PG. In particular, the data from the Hnr site represented Walker hybrid poplar growth during 11 growing seasons allowing for better parameterization of 3PG, compared to only 9 yr for the BH data. Additionally, because of the existing soil and climatic similarities (i.e. Hnr and BH sites) and dissimilarities (i.e., Hnr and ML sites) between the study sites (Table 1), it was logical to parameterize the 3PG model based on the Hnr data, and then test the model with data from a similar site (BH) as well as data from a dissimilar site (ML). Because at their current stand age these Walker trials do not provide sufficient information regarding within stand competition and its effects on biomass yields, the 3PG parameterization presented in this paper does not reflect any aspects of competition for light, water, and nutrients. However, as our stands develop and the effects of within stand competition could be measured, we intend to reflect this new knowledge in a future adaptation of the 3PG model for Walker stands.

Twelve of the 3PG variables in Table 2 were parameterized using Walker stand observations. The modeling data set was used to determine Walker tree allometric relationships and to predict tree mortality assuming that any tree deaths would occur within the first growing season (Table 2). Estimates for wood specific gravity of Walker trees were used from the literature [29,30]. Also based on studies from the literature, we determine the age of full canopy cover; the canopies of Walker trees in our stands were not yet fully closed at their current age. For example, the average tree crown diameter (standard error) of 12-yr old Walker hybrid poplars at the Hnr site was measured 2.35 (0.417), 2.61 (0.329), and 2.62 (0.350) m in stands established at spacing levels 2.4, 3.0, and 3.7 m, respectively (unpublished data). These measurements indicated that some Walker tree crowns may be touching in stands of 2.4 m spacing, suggesting partial crown closure at age 12 yr. Assuming that the ratio of tree height (m) to crown diameter (m) would be constant for hybrid poplars (derived from [31]), we computed the best approximation of age of full canopy cover using our annual tree height data from the Hnr site (Fig. 2) and assuming a ratio of 3.613:0.88 for Walker hybrid poplar tree height:crown diameter (derived from [26]). As a result, the age at full canopy closure used for 3PG model parameterization and evaluation in this paper was estimated at 12, 16, and 22 yr for Walker stands planted at 2.4, 3.0, and 3.7 m spacing levels, respectively (Table 2).

Eleven of the 3PG variables in Table 2 were parameterized with hybrid poplar data reported in the literature. We estimated the foliage:stem ratio at 2 and 20 cm of DBH using the relationship reported by Sand and Landsberg [22] and data from three separate hybrid poplar studies [32–34]. Hybrid poplar data from other studies were also used to determine the maximum and minimum fractions of net primary production allocated to roots [32,35], tree growth temperatures – minimum, optimum, and maximum [36], and specific leaf area [37]. Finally, nine other 3PG variables in Table 2 were parameterized by fitting model simulation results to Walker data from the Hnr site. We used the default 3PG values for the remaining 28 variables (Table 2).

We parameterized the Walker tree allometric equations for 3PG using tree density, height and DBH data from our modeling data set, a widely accepted hybrid poplar stem volume equation [14, p. 201], data from the literature for the fraction of above-ground biomass in branches [32–34], and Walker wood density of 0.358 g cm^{-3} [29,30]. The final parameters used in the allometric equations in the 3PG model [38] to predict tree height, $H\ (m) = a_H * (DBH,\ cm)^{n_{HB}} * (N,\ trees\ ha^{-1})^{n}_{HN}$, and stem volume, $V_s\ (m^3\ ha^{-1}) = a_V * (DBH,\ cm)^{n}_{VB} * (N,\ trees\ ha^{-1})^{n}_{VN}$, and above-ground biomass, $w_s\ (kg\ tree^{-1}) = a_s * (DBH,\ cm)^{n}_{s}$ were also reported in Table 2. Each of the constants in these equations, a_H, n_{HB}, n_{HN}, a_V, n_{VB}, n_{VN},

Table 2 – Walker-specific 3PG parameter estimates.

Parameter description (adapted from Sands [40])	3PG Symbol	3PGpjs name (see Sands [40])	Method of estimation	WALKER		References/Comments
				Value	Units	
Biomass partitioning and turnover						
Allometric relationships and partitioning						
Ratio of foliage:stem partitioning at DBH = 2 cm	p_2	*pFS2*	Observed: *Populus*	0.8567	–	[a]
Ratio of foliage:stem partitioning at DBH = 20 cm	p_{20}	*pFS20*	Observed: *Populus*	0.0590	–	[a]
Constant in stem mass versus DBH. relationship, w_s (kg tree^{-1}) = a_s * (DBH, cm)$^{n}_{s}$	a_S	*stemConst*	Observed: WALKER	0.0771	–	this study
Power in stem mass versus DBH. relationship	n_S	*stemPower*	Observed: WALKER	2.2704	–	this study
Maximum fraction of NPP to roots	h_{Rx}	*pRx*	Observed: *Populus*	0.34	–	Baker and Blackmon [32]
Minimum fraction of NPP to roots	h_{Rn}	*pRn*	Observed: *Populus*	0.13	–	Heilman et al. [35]
Litterfall and root turnover						
Litterfall rate at t = 0 yr	g_{F0}	*gammaF0*	Fitted	0	month^{-1}	
Litterfall rate for mature stands	g_{F1}	*gammaF1*	Fitted	0	month^{-1}	
Age at which litterfall rate has median value	t_{gF}	*tgammaF*	Fitted	0	month	
Average monthly root turnover rate	g_R	*Rttover*	Observed: *Populus*	0.005	month^{-1}	[b]
Growth modifiers						
Temperature modifier						
Minimum temperature for growth	T_{min}	*Tmin*	Observed: *Populus*	5	°C	[c]
Optimum temperature for growth	T_{opt}	*Topt*	Observed: *Populus*	20	°C	[c]
Maximum temperature for growth	T_{max}	*Tmax*	Observed: *Populus*	40	°C	[c]
Frost modifier						
Number of days production lost for each frost day	k_F	*kF*	Fitted	1	days	
Fertility modifiers (FR = fertility rating; between 0 and 1, with FR = 1 being very fertile)						
Value of m when FR = 0	m_0	*m0*	3PG default	0	–	Sands [40]
Value of f_N when FR = 0	f_{N0}	*fN0*	3PG default	1	–	Sands [40]
Power of (1 − FR) in f_N	n_{fN}	*fNn*	3PG default	0	–	Sands [40]
VPD modifier						
Defines stomatal response to VPD	k_D	*CoeffCond*	3PG default	0.05	mbar	Sands [40]
Soil water modifier						
Moisture ratio deficit which gives $f_q = 0.5$	c_q	*SWconst*	3PG default	depend on soil texture	–	[d]
Power of moisture ratio deficit in f_q	n_q	*SWpower*			–	[d]
Age modifier						
Maximum stand age used to compute relative age	t_x	*MaxAge*	3PG default	50	yr	Sands [40]
Power of relative age in f_{age} (use 0 to set $f_{age} = 1$)	n_{age}	*nAge*	3PG default	4	–	Sands [40]
Relative age to give $f_{age} = 0.5$	r_{age}	*rAge*	3PG default	0.95	–	Sands [40]
Stem mortality and self-thinning						
Seedling mortality rate (t = 0 yr)	g_{N0}	*gammaN0*	Observed: WALKER	0	yr^{-1}	[e]
Mortality rate for older stands (large t)	g_{N1}	*gammaNx*	3PG default	0	yr^{-1}	Sands [40]
Age at which $g_N = (g_{N0} + g_{N1})/2$	t_{gN}	*tgammaN*	3PG default	0	yr	Sands [40]
Shape of mortality response	n_{gN}	*ngammaN*	3PG default	1	–	Sands [40]

Maximum stem mass per tree at 1000 trees ha^{-1}	w_{Sx1000}	*wSx1000*	Fitted	200	kg/tree	
Power in self-thinning law	n_N	*thinPower*	3PG default	1.5	–	Sands [40]
Fractions of foliage, root and stem	m_F	*mF*	3PG default	0	–	Sands [40]
biomass pools per tree on each dying tree	m_R	*mR*	3PG default	0.2	–	Sands [40]
	m_S	*mS*	3PG default	0.2	–	Sands [40]
Canopy structure and processes						
Specific leaf area						
Specific leaf area at stand age 0 yr	s_0	*SLA0*	Observed: *Populus*	10.8	$m^2\ kg^{-1}$	Gielen et al. [37]
Specific leaf area for mature aged stands	s_1	*SLA1*	Observed: *Populus*	10.8	$m^2\ kg^{-1}$	Gielen et al. [37]
Age at which specific leaf area = $(s_0 + s_1)/2$	t_s	*tSLA*	Observed: *Populus*	1	yr	Gielen et al. [37]
Rainfall interception						
Maximum fraction of rainfall intercepted by canopy	i_{Rx}	*MaxIntcptn*	3PG default	0.15	–	Sands [40]
LAI for maximum rainfall interception	L_{ix}	*LAImax-Intcptn*	3PG default	0	$m^2\ m^{-2}$	Sands [40]
Light interception, production and respiration						
Extinction coefficient for PAR absorption by canopy	k	*k*	3PG default	0.5	–	Sands [40]
Age at full canopy cover	t_c	*fullCanAge*	Observed: WALKER	0	yr	[f]
Maximum canopy quantum efficiency	α_{Cx}	*alpha*	Fitted	0.0177	–	
Ratio NPP/GPP	Y	Y	3PG default	0.47	–	Sands [40]
Conductance						
Maximum canopy conductance	g_{Cx}	*MaxCond*	3PG default	0.02	$m\ s^{-1}$	Sands [40]
Canopy LAI for maximum canopy conductance	L_{Cx}	*LAIgcx*	3PG default	3.33	$m^2\ m^{-2}$	Sands [40]
Canopy boundary layer conductance	g_B	*BLcond*	3PG default	0.2	$m\ s^{-1}$	Sands [40]
Wood and stand properties						
Branch & bark fraction						
Branch and bark fraction at stand age 0 yr	p_{BB0}	*fracBB0*	Fitted	0	–	[g]
Branch and bark fraction for mature aged stands	p_{BB1}	*fracBB1*	Fitted	0	–	[g]
Age at which $p_{BB} = (p_{BB0} + p_{BB1})/2$	t_{BB}	*tBB*	Fitted	0	yr	[g]
Basic density						
Minimum basic density – for young trees	r_0	*rhoMin*	Observed: WALKER	0.358	$t\ m^{-3}$	Schroeder [30]
Maximum basic density – for older trees	r_1	*rhoMax*	Observed: WALKER		$t\ m^{-3}$	and Morrison et al. [29]
Age at which $r = (r_0 + r_1)/2$	t_r	*tRho*	3PG default	4	yr	Sands [40]
Stem height allometric relationship, $H\ (m) = a_H{}^*(DBH, cm)^{n_{HB}}{}^*(N, trees\ ha^{-1})^{n_{HN}}$						
Constant in stem height relationship	a_H	*aH*	Observed: WALKER	0.9740	–	this study
Power of DBH in stem height relationship	n_{HB}	*nHB*	Observed: WALKER	0.6816	–	this study
Power of stocking in stem height relationship	n_{HN}	*nHN*	Observed: WALKER	0.1064	–	this study
Stem volume allometric relationship, $V_s\ (m^3\ ha^{-1}) = a_V{}^*(DBH, cm)^{n_{VB}}{}^*(N, trees\ ha^{-1})^{n_{VN}}$						
Constant in stem volume relationship	a_V	*aV*	Observed: WALKER	0.0001	–	this study
Power of DBH in stem volume relationship	n_{VB}	*nVB*	Observed: WALKER	2.3270	–	this study
Power of stocking in stem volume relationship	n_{VN}	*nVN*	Observed: WALKER	1.0915	–	this study
Conversion factors						
Intercept of net radiation versus solar radiation relationship	Q_a	*Qa*	3PG default	−90	$W\ m^{-2}$	Sands [40]
Slope of net radiation versus solar radiation relationship	Q_b	*Qb*	3PG default	0.8	–	Sands [40]

(*continued on next page*)

Table 2 (continued)

Parameter description (adapted from Sands [40])	3PG Symbol	3PGpjs name (see Sands [40])	Method of estimation	WALKER		References/ Comments
				Value	Units	
Molecular weight of dry matter		*gDM_mol*	3PG default	24	$g\,mol^{-1}$	Sands [40]
Conversion of solar radiation to PAR		*molPAR_MJ*	3PG default	2.3	$mol\,MJ^{-1}$	Sands [40]

a Parameters *pFS2* and *pFS20* were estimated from eq.A.8 in Sand and Landsberg [22], which we parameterized with observation data from poplar trials in the literature [32–34]. Detailed descriptions (and equations) of all 3PG parameters in this table can be found in the literature [18,21,22,38,40].
b We used a turnover rate of 6% yr^{-1} for hybrid poplar coarse roots (Welham et al. [52]; see their Table 1).
c We derived hybrid poplar growth temperatures from Drew and Chapman [36].
d Values for soil water modifiers (Swconst; Swpower) differed by soil texture class as follows: (0.7; 9) for sandy (S); (0.6; 7) for sandy loam (SL); (0.5; 5) for clay loam (CL); and (0.4; 3) for clay textures [40].
e We assumed that any tree mortality would occur within the first growing season; this was accounted for by adjusting the number of live trees per hectare and keeping all 3PG default values for stem mortality and self-thinning modeling.
f We determined the approximate age of Walker trees at full canopy cover for each spacing level (2.4, 3.0, and 3.7 m) assuming a ratio of 3.613:0.88 for tree height:crown diameter (derived from [26]) and using Walker tree height data by stand age (from our modeling data set); expected crown diameter (m) was estimated as tree height (m) * 0.88/3.613. Age at full canopy closure was estimated at 12, 16, and 22 yr for Walker stands planted at 2.4, 3.0, and 3.7 m spacing levels, respectively.
g We assigned a value of 0 to the branch and bark fraction parameters due to shown variation by stand age and site quality [22]. Surrogate estimation of these fractions was done via subtraction of stem-only mass (based on stem volume, Vs, estimation and wood density) from above-ground tree mass (w_s).

a_s, and n_s were calculated using the solver procedure in Microsoft Excel by fitting the Walker data from the Hnr site (modeling data set) to the allometric equations used in 3PG, which was done via multiple iterations so that the sum of the absolute difference between estimated and observed data was minimized. The Hnr site data that were used in the solver procedure included tree height, stem volume, stand density and above-ground biomass of all the individual trees from all stands of all ages and spacing levels. This analysis approach of fitting empirical data to specific allometric equations was similar to the methodology used in other modeling studies [13].

The 3PG model requires climate data as input [22,38], which are often available and can be obtained from permanent weather stations. We acquired daily climate data from weather stations closest to each of our study sites (Fig. 1); data were available online from the Canadian national climate data center [39]. These data were then averaged for each month for the period from January 1997 to December 2007: minimum, maximum, and average monthly air temperature (°C), monthly rainfall (mm), number of rain and frost days per month. Direct measurements of vapor pressure deficit (VPD, mbar) were not available from these weather stations and VPD was estimated as half the difference between the saturated vapor pressure at the minimum and maximum daily temperatures [40]. Solar radiation data ($MJ\,m^{-2}\,day^{-1}$) were also not available from the permanent weather stations near our study sites, so we computed average daily solar radiation using the Thornton-Running model [41,42]. We used a software package developed by P.E. Thornton (MT-CLIM for Excel, available online (verified on October, 03, 2008): from http://www.ntsg.umt.edu/bioclimatology/mtclim) to produce solar radiation estimates based on site latitude, altitude, and daily precipitation and minimum and maximum temperatures. Although the 3PG model can be run using long-term monthly averages, we used actual monthly weather data to account for drought events (or relatively low precipitation), in particular, combined with periods of relatively high mean temperature and high solar radiation that occurred during the summer months of 2001 and 2002 at our sites (Fig. 3).

Because of the complexity of soil-plant-atmosphere interactions within a forest stand, a proper method for parameterization of the fertility rating (FR) variable in 3PG was not available [21]. Landsberg et al. [21] summarized the problems associated with the FR variables stating that "…the widespread inadequacy of soil survey data and our poor quantitative understanding of the relationships between soil chemical properties…and plant growth make it difficult to establish clear quantitative guidelines for selecting FR values…" Corroborating with the latter statement were the results by Pinno [43], who analyzed data from 4-yr old hybrid poplar stands to predict forest productivity using soil and site information. In addition, Pinno [43] reported that the relationship between soil and site properties and hybrid poplar growth could also vary depending on the scale of analysis, i.e., at the local scale (across a landscape) versus the microsite scale (within a forest stand). Because of the uncertainties associated with parameterization of the FR variable as related to hybrid poplar growth, for the work in this paper, we used the hybrid poplar afforestation suitability index developed by Joss et al. [44] as a surrogate estimate of FR in the 3PG model.

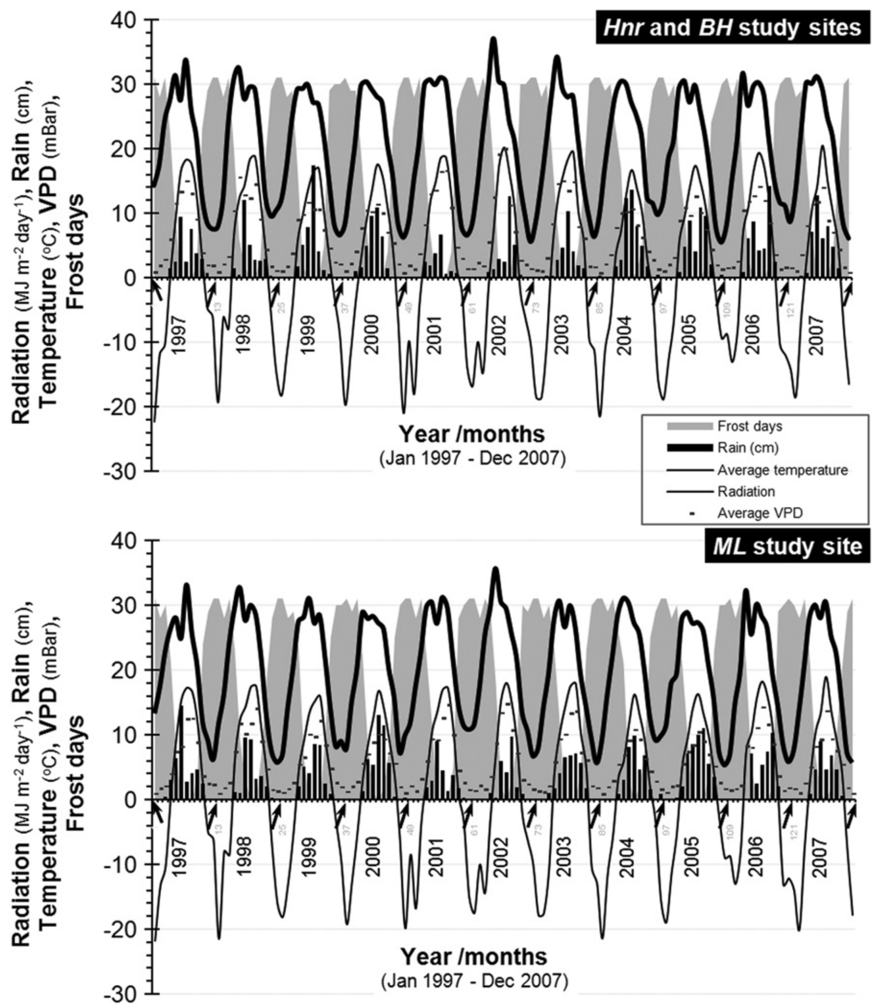

Fig. 3 – Ten-year climate data summary, from January 1997 to December 2007, for three Walker hybrid poplar sites in central Saskatchewan, Canada; Meadow Lake (ML), Henribourg (Hnr) site, and Birch Hills (BL) sites. Shaded area represents number frost days month^{-1}; columns indicate monthly precipitation as rain (cm), graphed in cm for better presentation; thin line indicates monthly mean temperature (°C); thick line indicates monthly mean daily solar radiation (MJ m^{-2} day^{-1}); rectangular symbols indicate monthly mean vapor pressure deficit (VPD, mBar; 10 mBar = 1 kPa); and arrows along the x-axis mark each year's beginning.

Joss et al. [44] used a fuzzy logic modeling approach to estimate afforestation suitability as an index value between 0 and 1(1 being the best and 0 – the worst), similar to the FR variable in the 3PG model. They utilized data for five environmental variables and their ranges from numerous hybrid poplar stands across the Prairie Provinces of Canada (based on a large inventory of hybrid poplar afforestation projects in this region). As a result, the assigned FR values were 0.4582 (Hnr site) for the 3PG model parameterization and sensitivity analysis work in this paper, and FR of 0.4982 (ML site) and 0.5155 (BH site) for the site-specific 3PG model evaluation work.

Finally, we used available soils data [45] to parameterize the available soil water (ASW), and soil texture class variables required by 3PG. Assigned soil texture classes were sandy loam (Hnr and ML sites), and clay loam (BH site). The range of ASW was from 100 to 150 mm (Hnr site), and from 150 to 200 mm (ML and BH sites).

2.3. 3PG model performance evaluation

We evaluated the performance of the 3PG model that was specifically parameterized to predict Walker tree growth, as described above, against empirical data from our testing Walker data set, i.e., data from the BH and ML sites. We used height and DBH measurements from our testing data set to compute the bias of 3PG predictions, as well as the R-square of linear regressions of predicted (dependent variable) versus observed (independent variable) data. To account for any effects of initial tree density on Walker growth predictions made by the 3PG model, we performed separate evaluation analyses with observation data from each of the testing study sites and for different tree spacing levels. These model evaluation techniques (bias and R-square estimates) were analogous to methods used in other studies [41].

We estimated bias as the sum of the absolute difference between predicted and observed values, divided by the number of observations; *Bias* = *(SUM(predicted − observed))/number observations*. The R-square of the linear regressions were estimated in Microsoft Excel by adding a trendline for multiple data points in a graph depicting predicted versus observed data; the linear regression models were of the following general form, *predicted* = *a* * *observed* + *b*, where *a* and *b* were model coefficients.

2.4. *Model sensitivity analysis*

Due to scarcity of Walker hybrid poplar data in the literature, we parameterized some of the 3PG model variables based on data from *P. deltoides* studies from the literature, or they were based on certain assumptions (Table 2). For these reasons, we performed sensitivity analyses to assess the effects of relative changes in these variables on 3PG predictions. Nine of the 3PG parameters that we varied in our analyses were as follow (refer to column 3PGpjs name in Table 2): *pFS2*, *pFS20*, *pRx*, *pRn*, *Rttover*, *Topt*, *SLA0*, *SLA1*, and *fullCanAge*; the latter was based on assumed tree height:crown diameter relationship for Walker trees derived from PFRA [26]. The other two parameters were FR (i.e., fertility rating) and the lower limit of ASW (i.e., minimum available soil water).

We varied (increase and decrease) each parameter by 5, 20, and 40% of their current value while holding all other parameters unchanged to estimate the relative change in predicted mean DBH and height for a Walker stands relative to empirically measured DBH and height. For this analysis we used data at age 11 yr from the modeling data set (Hnr site) for trees planted at 2.4 m spacing. Eleven years was the upper range of stand ages in this data set and was approximately representing mid-rotation of Walker stands. Although rotation lengths for hybrid poplar bioenergy production systems have not yet been established, they could vary depending on soil and climatic conditions, as well as management treatments (i.e., fertilization and irrigation). It was shown that hybrid poplar rotations could vary between 15 and 25 yr when trees are grown for pulpwood production, and for larger size trees (saw-logs) rotations could be even longer, 20–30 yr [14].

3. Results and discussion

3.1. *3PG model parameterization*

The modeling data set (i.e., from Hnr site) used for 3PG parameterization consisted of 2232 data records, each including height and DBH measurements from stands established at three density levels (2.4, 3.0, and 3.7 m) for Walker hybrid poplar trees ranging from 6 to 11 yr old. Mean values (analyzed by age) for tree height at Hnr ranged from 4.9 to 9.5 m, and mean DBH ranged from 4.7 to 9.7 cm between stand age 6 and 11 yr (Fig. 2). Although some trees measured up to nearly 14 m in height or up to 18.7 cm in DBH at age 11 yr, other individual trees were 3 m in height, or 1.7 cm in DBH at the same age. These broad height and DBH variations observed at the Hnr site provided a broad basis for tree height, stem volume, and tree biomass model parameterization (as a function of DBH and tree density) and, thus, making the 3PG model better suited for Walker hybrid poplar growth predictions under varying growth conditions.

The above-ground biomass model in Fig. 4 showed that tree biomass (stem, bark and branches included) increased exponentially as tree DBH increased with stand age, averaging at approximately 13 kg tree^{-1} at age 11 yr (i.e., at mean DBH of 9.7 cm observed at age 11 yr). The bias of this model was estimated at −0.038 kg tree^{-1}, with an absolute difference between predicted and observed biomass averaging 0.797 kg tree^{-1}. The tree height model in Fig. 5 also indicated a positive correlation of tree height and DBH. The effects of modeling tree height as a function of tree spacing, in addition to DBH, were less apparent in this model showing that tree height would average 9.3, 9.6, and 10.1 m at 11 yr (i.e., at mean DBH of 9.7 cm) in stands established at 3.7, 3.0, and 2.4 m tree spacing levels, respectively. However, the tree height model clearly showed a trend that tree height would increase as tree density increased (i.e., tree spacing decreased), all resulting from increased competition for light between trees growing closer together at higher tree densities. The bias of the tree height model was −0.036 m, with an absolute difference between predicted and observed tree height averaging 0.58 m.

The stem volume model in Fig. 5 resembled an exponential function, and was similar to the tree biomass model (Fig. 4). On one hand, stem volume estimates (m^3 ha^{-1}) were very similar to tree biomass estimates (kg tree^{-1}) in that they both included the same components of a tree except that stem volume estimates excluded bark and branches. On the other hand, stem volume estimates represented biomass volume at a stand level, as opposed to individual trees and, thus, these estimates were affected by tree density (Fig. 5). The effects of tree spacing on stem volume predictions were such that at age 11 yr (i.e., at mean DBH of 9.7 cm), stem volume averaged 23.9, 35.6, and 58.0 m^3 ha^{-1} at 3.7, 3.0, and 2.4 m spacing,

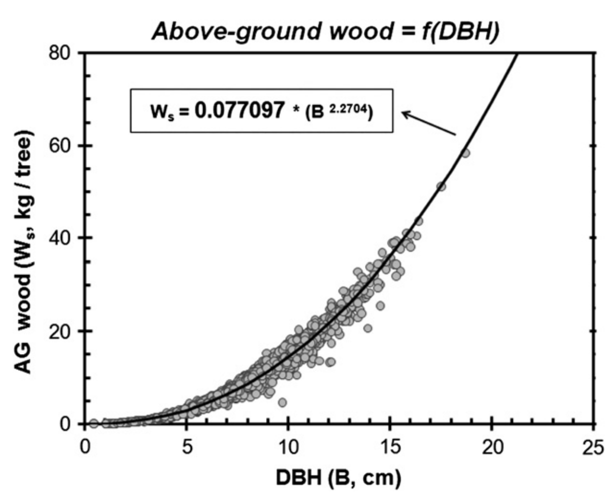

Fig. 4 – Above-ground biomass model estimates (kg tree^{-1}, including stem and branches) for Walker hybrid poplar trees developed as a function of tree DBH (cm) plotted along with empirical data (filled circles in graph) measured from a Walker trial at a site near Henribourg (Hnr) in central Saskatchewan, Canada. These data were also used as a modeling data set for 3PG model parameterization for Walker trees.

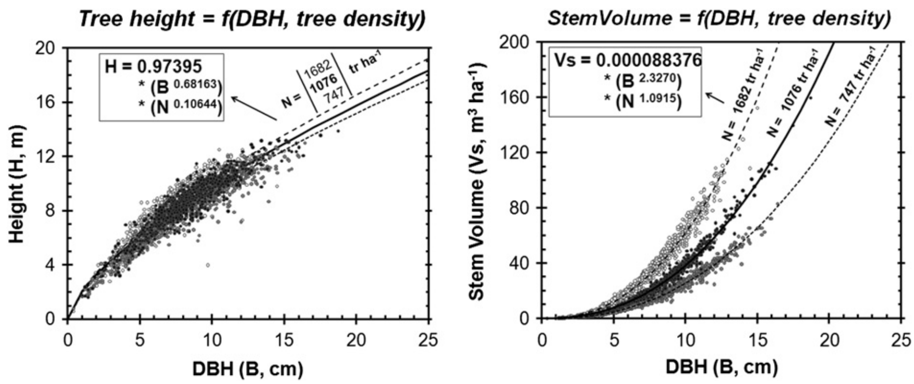

Fig. 5 – Tree height (m), left graph, and stem volume (m^3 ha^{-1}), right graph, models for Walker hybrid poplar trees developed as a function of tree density (N, trees ha^{-1}) and DBH (cm). Empirical data (circles in both graphs) were obtained from a study site near Henribourg (Hnr) in central Saskatchewan, Canada within stands established at three levels of tree density – N equal to 1682 trees ha^{-1} (white circles), 1076 trees ha^{-1} (dark circles), and 747 trees ha^{-1} (grey circles). These data were fit to the models shown on the graphs and used to parameterize the 3PG model for Walker trees.

respectively. The significant differences between stem volume estimates at different tree spacing levels was likely a direct result of the different number of trees per hectare; as tree spacing decreased and number of trees per hectare increased, i.e., tree density increased, stem volume also increased (Fig. 5). However, based on well-known self-thinning rules in forest stands [46], it is expected that fewer number trees would survive and continue growing at a certain limiting level of tree density. As a consequence, it is expected that as the number of trees per hectare increased so would tree mortality which would offset further stem volume increase at the stand level. Due to the complex interactions between trees within a stand in regard to resource allocation and full site occupancy, empirical data for tree size, tree density, and tree mortality should all be included in tree growth prediction models [47].

Using the 3PG parameter values in Table 2, we predicted mean tree height and mean DBH for Walker hybrid poplar trees and we compared these results with observations from our modeling data set for each tree spacing level, 2.4, 3.0, and 3.7 m; results for the 2.4-m spacing are shown in Fig. 6. This comparison analysis was done to establish a performance baseline of 3PG for Walker growth predictions when the 3PG model was used to predict tree growth in stands from which

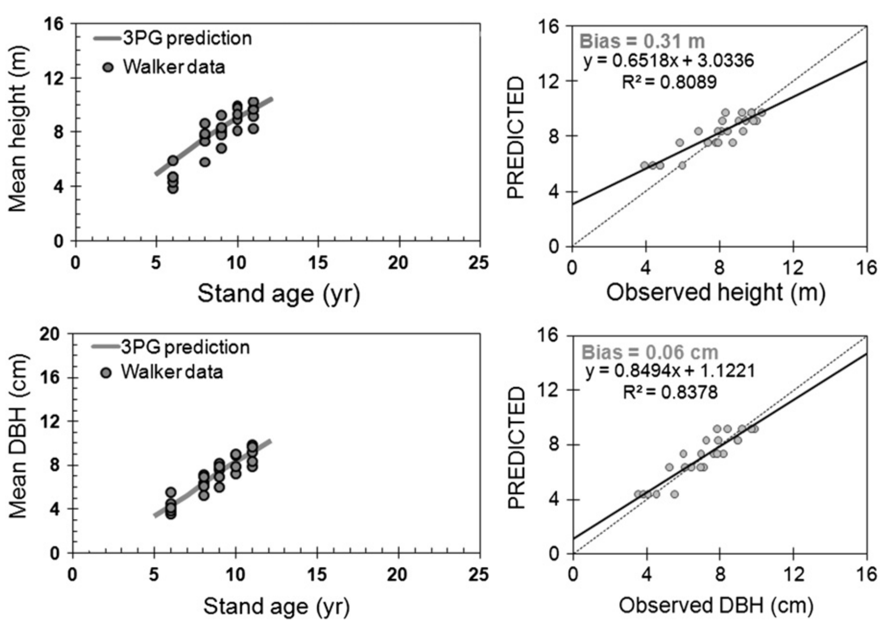

Fig. 6 – Walker hybrid poplar predictions by stand age (from 3PG model) of tree height (m) and DBH (cm) plotted along with empirical data from stands established at 2.4 m spacing near Henribourg (Hnr) in central Saskatchewan, Canada (modeling data set), left two graphs. Right two graphs show the same height and DBH data presented as predicted (from 3PG model) versus observed. Dashed lines represent the potential 1:1 relationship between predicted and observed values, and the solid line represents a linear regression of model predictions as a function of observed values.

empirical data were used for 3PG parameterization. Results from a more vigorous 3PG model testing done against two independent Walker data sets (i.e., testing data sets from BH and ML sites) are presented later in the text.

The 3PG performance baseline results showed that there was positive bias for Walker tree height and DBH predictions (Fig. 6, Table 3). Tree height bias ranged from 0.19 to 0.64 m, and DBH bias ranged from 0.00 to 0.46 cm. The highest regression R-square values were estimated for height and DBH predictions made at 2.4 m spacing, 0.81 and 0.84, respectively (Fig. 6, Table 3). The R-square values for the remaining spacing levels were between 0.54 and 0.61 (Table 3). The 3PG model tended to overestimate tree height at younger stand ages for the 2.4-m spacing level (Fig. 6) which was likely the reason for the overall positive bias of these predictions. This trend was less apparent at the other spacing levels due to the higher variation of our height observations evident from the relatively lower regression R-square values (Table 3).

There are multiple benefits of parameterizing the 3PG model for fast-growing hybrid poplar clones, such as the Walker variety. The most important advantage of this model is that long-term biomass supply data could be predicted and made available to farmland owners and industries that are willing to grow hybrid poplar on agricultural land for bioenergy production. Biomass flow data from a hybrid poplar stands could then be used for a variety of decision-making tasks such as harvest time and intensity, depending on market conditions. However, in order to parameterize the 3PG model for a full rotation length of hybrid polar cultures, and to validate any predictions, the initial parameterization work presented in this paper must be expanded further. A main focus of improving the model would be obtaining data to adequately simulate stand mortality (due to within stand competition) in short-rotation hybrid poplar bioenergy systems. Such data are currently not available in the literature. Another aspect of improving the model's performance would be to parameterize all variables used by 3PG, as listed in Table 2, with empirically derived data.

The weaknesses of the 3PG model in regards to Walker tree growth predictions stem from the fact that 3PG was designed for use in stands of evergreen species, such as eucalyptus and pines [20,22]. Therefore, litterfall equations that were used in 3PG were not intended for deciduous species with annual litterfall events, such as poplar. Also, tree mortality modeling in the presently available version 2.5 of the 3PGpjs software (3PG model based on Microsoft Excel worksheets and coded in Visual Basic programming language) was not simulated as a function of soil and climatic conditions [38,40]. Finally, in order to predict biomass production in Walker stands which could be partially thinned (or damaged), new allometric relationships must be developed between mean stand DBH, tree density, tree biomass, stem volume, and tree height, all based on new stand observations (refer to Table 2).

3.2. *3PG model performance evaluation against independent Walker data sets*

The results from 3PG performance evaluation analyses done against two independent Walker data sets, each including height and DBH data from stands established at three spacing levels (2.4, 3.0, and 3.7 m), showed both positive and negative bias of model predictions (Fig. 7, Table 3). Across all spacing levels at the two sites, bias of tree height predictions ranged from −1.76 to 1.45 m, and bias of DBH predictions ranged from −2.61 to 0.66 cm. Regression R-square values of 3PG-predicted versus observed tree height and DBH were similar across the two model testing sites and across tree spacing levels and ranged from 0.75 to 0.98 (Table 3).

The performance of the 3PG model was superior for the BH site. Overall, tree height and DBH prediction bias was within 1.5 m and 0.7 cm, respectively. These results were consistent across spacing levels and stand age; data for 2.4-m spacing were shown in Fig. 7. The 3PG predictions for tree height and DBH at the ML site were consistently lower than observed measurements, with an estimation bias up to 2.6 cm DBH and 1.8 m tree height (Fig. 7, Table 3). For the three spacing levels at ML, the 3PG model underestimated Walker DBH across all stand ages (Fig. 7) with no observable trend. In comparison, the 3PG model predictions for Walker tree height were relatively closer to observed data in younger stands (<7 yr) in

Table 3 – 3PG model performance evaluation results for bias and R-square values from regressions analyses of predicted (dependent variable) versus observed (independent variable) estimates of tree height (m) and DBH (cm) for Walker hybrid poplar. Empirical data were used for 3PG model parameterization and model performance testing from three study sites, established at three tree spacing levels (2.4, 3.0, and 3.7 m) in central Saskatchewan, Canada; Henribourg site, Hnr; Birch Hills site, BH; and Meadow Lake site, ML.

Site	Spacing (m)	Tree height (m)		DBH (cm)	
		Bias (m)	R-sq	Bias (cm)	R-sq
Hnr (modeling set)	2.4	0.31	0.81	0.06	0.84
	3.0	0.19	0.61	0.00	0.54
	3.7	0.64	0.61	0.46	0.58
BH (testing set)	2.4	0.97	0.80	0.01	0.86
	3.0	1.45	0.87	0.66	0.92
	3.7	0.69	0.75	−0.09	0.80
ML (testing set)	2.4	−1.56	0.96	−2.19	0.98
	3.0	−1.76	0.95	−2.61	0.96
	3.7	−1.61	0.96	−2.34	0.96

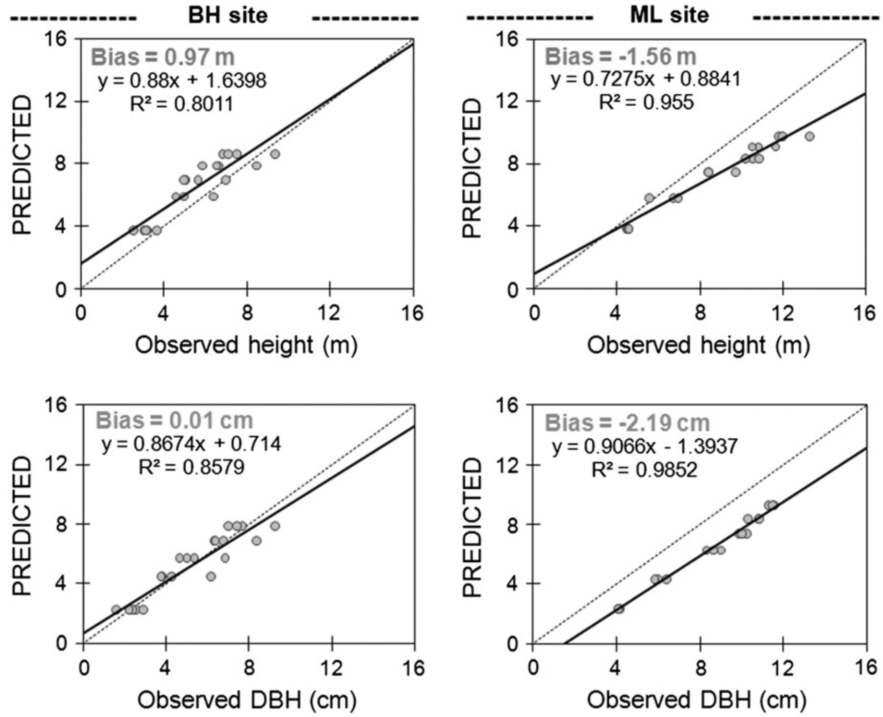

Fig. 7 – Predicted (from 3PG model) versus observed tree height (m) and DBH (cm) data for Walker hybrid poplar; empirical data were obtained from stands established at 2.4 m spacing at two study sites – near Birch Hills (BH), left two graphs, and Meadow Lake (ML), right two graphs, located in central Saskatchewan, Canada. Dashed lines represent the potential 1:1 relationship between predicted and observed values, and the solid line represents a linear regression of model predictions as a function of observed values.

which mean tree height was up to 7 m, at all three spacing levels, which was also depicted in Fig. 7 for stands established at 2.4 m spacing. However, in older stands (>7 yr) with mean tree height greater than 7 m, the 3PG model underestimated tree height with a trend indicating larger tree height underestimation as stands aged.

Because of data scarcity from long-term Walker hybrid poplar studies, there may be some uncertainties associated with 3PG predictions of height and DBH. The source of these prediction uncertainties could be traced to the original data that were used for 3PG model parameterization. For example, available soil water as well as tree mortality both could be affected in the long-term by the presence of competing vegetation such as grass and brush species volunteering in the understory of Walker stands. As a result of such competition for site resources (soil water and nutrients in this case), available soil water used by Walker trees could be limited and, thus, lead to reduced overall tree growth rate and could result in increased tree mortality when these restrictions last for prolonged periods. Subsequently, the effects of limited available soil water for Walker tree growth would propagate to a number of stand variables used by the 3PG model, all of which could affect model predictions; e.g., foliage:stem ratios (i.e., pFS2 and pFS20), proportion of NPP allocated to roots (i.e., pRx and pRn), as well as age of full canopy cover (i.e., fullCanAge) (Table 3).

In general, tree mortality reflects the state of balance between site resources including soil and climate characteristics, and site occupancy by trees, i.e. number of trees per unit area [47]. Mortality would be minimal when the entire community of growing trees had access to more site resources than they required at their present stage of development; however, mortality would increase if site occupancy exceeded site resources, thus resulting in self-thinning [47]. Although it is logical to expect higher biomass yield from a stand with more stems per hectare (i.e., higher tree density), higher tree mortality could offset these biomass additions. For example, studies on biomass production from short-rotation crop systems using willow species, usually managed at 3–5 yr rotations, showed that biomass yield was not affected by tree density beyond a certain limit, about 20 000 stems ha^{-1} [48,49]. Wilkinson et al. [49] also emphasized the fact that at higher tree densities smaller diameter stems were produced (albeit a larger number of them), which may result in a relatively larger fraction of bark in total biomass. From a bioenergy production aspect, because of the different properties of stem wood and bark, the energy output efficiency from both biomass components would be very different [49].

We believe that the 3PG model could be much improved if more information were available from older Walker stands grown in short-rotation crop systems. Additional data showing the range of tree density for which Walker biomass yield would be affected (at a stand level), long-term available soil water, as well as tree mortality data for varying stand establishment spacing levels, all would enhance the performance of the 3PG model for Walker hybrid poplar growth prediction.

Table 4 – Sensitivity analysis results for Walker hybrid poplar height and DBH predictions, shown as percent decrease or increase from the average of observed values at age 11 yr, produced by the 3PG model assuming 5, 20, and 40% decrease and increase of the value of eleven 3PG model parameters: pFS2 and pFS20 – ratios of foliage:stem partitioning at DBH 2 and 20 cm, respectively; pRx and pRn – maximum and minimum fraction of NPP to roots, respectively; Rttover – average monthly root turnover rate; Topt – optimum temperature for growth; SLA0 and SLA1 – specific leaf area for young and mature stands, respectively; fullCanAge – age at tree canopy closure; FR – fertility rating; minASW – minimum available soil water capacity. This analysis was based on data from the Hnr site at the 2.4 m spacing level. Shaded values indicate decrease or increase > 5%, and bolded values: > 10%.

3PG variable	Walker parameter		Walker parameter value change					
	value	units	−40%	−20%	−5%	+5%	+20%	+40%
Decrease (-) or increase (%) of Height; DBH predictions at age 11 yr								
pFS2	0.857	–	1.9; 0.7	3.1; 2.4	3.2; 2.6	2.9; 2.2	2.4; 1.4	1.5; 0.1
pFS20	0.059	–	4.1; 3.9	3.6; 3.1	3.2; 2.6	3; 2.2	2.6; 1.7	2.2; 1.1
pRx	0.340	–	6.1; 6.9	4.5; 4.4	3.4; 2.9	2.8; 1.9	1.9; 0.7	0.8; −0.9
pRn	0.130	–	5.9; 6.6	4.3; 4.3	3.4; 2.8	2.8; 2	2; 0.9	1.1; −0.5
Rttover	0.0050	$month^{-1}$	3.1; 2.4	3.1; 2.4	3.1; 2.4	3.1; 2.4	3.1; 2.4	3.1; 2.4
Topt	20	°C	5.7; 6.3	7.2; 8.5	4.4; 4.3	1.7; 0.4	−3; −6.4	**−10.3; −16.5**
SLA0	10.8	$m^2 kg^{-1}$	2.8; 2.1	3; 2.2	3; 2.4	3.1; 2.4	3.2; 2.5	3.3; 2.7
SLA1	10.8	$m^2 kg^{-1}$	−3.9; −7.6	0.8; −.9	2.7; 1.9	3.3; 2.8	3.8; 3.4	4.2; 4
fullCanAge	12	yr	**14.3; 19.2**	**9.4; 11.7**	4.6; 4.7	1.6; 0.3	−2.4; −5.5	**−7; −11.9**
FR	0.4582	–	1.4; 0	2.3; 1.3	2.9; 2.1	3.2; 2.7	3.7; 3.4	4.3; 4.2
minASW	100	mm	−5.1; −.9.2	1.1; −.0.4	2.6; 1.7	3.5; 3	4.5; 4.4	5.1; 5.3

3.3. *3PG model sensitivity analysis*

In order to identify the relative influence of different model variables on prediction results for Walker hybrid poplar (height and DBH), we ran separate 3PG model simulations. These simulations were based on 5, 20, and 40% change (increase and decrease) of eleven 3PG parameter values, so that for each simulation only one parameter value was changed and the rest were kept unchanged (Table 4). Overall, depending on the magnitude of change of 3PG parameter values, the effects on height predictions at age 11 yr ranged from −10.3% (indicating underestimation) to 14.3% (i.e., overestimation) and ranged from −16.5 to 19.2% for DBH predictions.

Any changes in pFS2 and pFS20 ratios (increase and decrease) resulted in higher height and DBH predictions, and the main differences were in the magnitude of the increase of these predictions (Table 4). A decrease in the parameter values of either the pFS2 or pFS20 ratios would result in higher height and DBH predictions compared to predictions resulting from increased parameter values of these two ratios. This relationship was biologically reasonable and depicted how the processes embedded in the 3PG model controlled tree biomass production based on parameter values. For lower pFS20 values, more biomass would be allocated to the stem and less to foliage, resulting in higher height and DBH estimates.

Deviations of pRx and pRn (i.e., maximum and minimum fractions of NPP allocated to roots) resulted in similar changes in height and DBH estimates (Table 4). As the values of these parameters increased, i.e., more biomass was allocated to roots and less to the stem, height and DBH estimates decreased. The reverse was also logical – as pRx and pRn decreased, i.e., less biomass was allocated to roots, tree height and DBH predictions increased. As trees grow and more biomass is being accumulated, the proportion allocated to roots also changes. Research showed that as hybrid poplar stands developed, the biomass was preferentially allocated to stems and branches when compared to root biomass [50]. Wullschleger et al. [50] reported that, in general, about 62% of total hybrid poplar biomass (*Populus trichocarpa* x *P. deltoides clone*) was distributed to shoots and 38% to roots during the establishment year, while 79% was distributed to shoots and about 21% to roots in 2-yr old trees.

Our sensitivity analysis results indicated that the most pronounced effects on Walker hybrid poplar height and DBH predictions could be due to parameterizing the optimum temperature for growth (Topt), surface leaf area for mature stands (SLA1), age of canopy closure (fullCanAge), and minimum available soil water capacity (minASW) (Table 4). As the value of Topt decreased by 20%, height and DBH predictions increased by 7.2 and 8.5%, respectively. In contrast, any increase in Topt resulted in a decrease up to 10.3 and 16.5% of height and DBH predictions, respectively. This relationship was in accord with findings from other studies [36] that showed higher biomass production in northern latitudes (i.e., lower average daily temperatures) by hybrid poplar clones that were relatively more cold-tolerant.

Decreasing the value of the SLA1 parameter resulted in different changes in 3PG predictions. The magnitude of deviation of height and DBH due to SLA1 change was <=4.2% for any of the scenarios analyzed (increase or decrease) except for the 40% decrease for which DBH decreased by 7.6% (Table 4). Reduction in the value of fullCanAge by 40% increased height (14.3%) and DBH (19.2%) predictions; the reverse relationship was also significant – height and DBH decreased as fullCanAge increased. In particular, as height and DBH increased, most likely due to better tree growth conditions (i.e., more suitable soil, site, and climatic characteristics), the tree canopy closed sooner (i.e., lower fullCanAge value); faster canopy closure would be the obvious result of better tree growth. In comparison, if fullCanAge was 40% larger, i.e., much longer time was needed for trees to close canopy, then it would be expected that trees would grow slower (i.e., decreased height and DBH) likely due to poor growing conditions.

Finally, changes in height and DBH were positively correlated with changes in the values of FR and minASW variables in the 3PG model (Table 4). Even 40% deviation in the value of FR resulted in <=4.3% deviation in height and DBH estimates. However, the effects of minASW deviations on tree height and DBH were more appreciable – up to 5.1 and 9.2% decrease, respectively, when minASW was decreased by 40%. These results depicted some of the effects of soil properties (nutrients and water) on tree growth with emphasis on soil water, which appeared to play a more significant role in tree growth than the overall fertility rating of the site.

It is reasonable to expect that 3PG performance for Walker hybrid poplar growth prediction could be maximized when all species-specific parameters in Table 2 were parameterized based on empirical observations. However, as shown in Table 4, significant deviations in the values of some 3PG parameters would result in relatively minimal (<5%) change in predicted tree height and DBH. In contrast, significant deviations of other parameter values in 3PG, such as pRx, pRn, Topt, SLA1, fullCanAge, and minASW (Table 4) could result in up to 19% deviation of height and DBH predictions (Table 4). Therefore, it would be more practical to allocate research time and resources to study and better parameterize the above six 3PG variables instead of spreading resources across many 3PG variables.

4. Conclusions

Establishing hybrid poplar plantations, such as Walker hybrid poplar, for bioenergy production on underutilized agricultural land across Saskatchewan, and other Prairie Provinces in Canada, provides many benefits for society and the environment. Hybrid poplar biomass could be used as fuel when burned for heat and electricity production (when used with coal), or when used for ethanol production. An important aspect of hybrid poplar biomass production systems is that they could be established on underutilized (marginal) agricultural lands thus providing additional financial flow for the farmer. Finally, when biomass is used for energy production, the CO_2 emitted into the atmosphere during biomass burning will be sequestered back into the tree components (stem, foliage, roots) and stored in the soil as soil organic carbon, during the development of future hybrid poplar stands. In a summary of the global carbon cycle, Schlesinger [51] suggested that the potential for enhanced carbon sequestration in terrestrial ecosystems is much greater in forest vegetation than in soils, which would make reforestation and afforestation attractive short-term practices for atmospheric CO_2 sequestration on land.

To aid farmers and industries willing to grow Walker hybrid poplar for biomass production, we parameterized the 3PG model. Bias of 3PG estimates ranged from −1.76 to 1.45 m for tree height, and from −2.61 to 0.66 for DBH predictions made for stands established at three levels of tree spacing (2.4, 3.0, and 3.7 m). Our results indicated that, once parameterized for a specific hybrid, the 3PG model could be successfully used to predict hybrid poplar growth with desirable accuracy for agricultural land in Saskatchewan.

Acknowledgements

We wish to recognize R. Nedsdoly of Mistik Management Ltd, Weyerhaeuser Canada, and J. Kort of AAFC-PFRA Shelterbelt Centre for the installation of these spacing trials, and funding from the Saskatchewan Forest Centre Forest Development Fund, Natural Science and Engineering Research Council of Canada and the AFIF Chair in Agroforestry and Afforestation. We thank Brent Joss and other researchers from the Canadian Wood Fibre Centre at Natural Resource Canada of the Canadian Forest Service for providing afforestation suitability data. We also thank Doug Jackson of University of Saskatchewan for all field data collection.

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