Ecological Modelling 222 (2011) 2249–2261

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Development of TRIPLEX-Management model for simulating the response of forest growth to pre-commercial thinning

Weifeng Wang[a], Changhui Peng[a,*], S.Y. Zhang[b], Xiaolu Zhou[a], Guy R. Larocque[c], Daniel D. Kneeshaw[a], Xiangdong Lei[a,d]

[a] *Institut des Sciences de l'Environnement, Département des Sciences Bioloqiues, Université du Québec à Montréal (UQAM), Montréal, QC H3C 3P8, Canada*
[b] *FPInnovations, Forintek Division, 2665 East Mall, Vancouver, BC V6T 1W5, Canada*
[c] *Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, PO Box 3800, 1055 du P.E.P.S., Stn. Sainte-Foy, Quebec, QC G1V 4C7, Canada*
[d] *Institute of Forest Resource Information Techniques, Chinese Academy of Forestry, Beijing 100091, China*

ARTICLE INFO

Article history:
Available online 10 October 2010

Keywords:
Biomass
Diameter distribution
Forest management
Timber yield
Weibull distribution

ABSTRACT

In order to simulate forest growth response to pre-commercial thinning (PCT), TRIPLEX1.0 – a process-based model designed to predict forest growth as well as carbon (C) and nitrogen (N) dynamics – was modified and improved to also simulate managed forest ecosystem thinning practices. A three-parameter Weibull distribution model was integrated to simulate thinning treatments within the newly developed TRIPLEX-Management model. The thinning intensity component within the model allows users to simulate thinning treatments by applying basal area, stand density and volume to quantify thinning intensity. Natural mortality decreased following thinning due to an increase in growing space for residual stems. Predicted litterfall pools also increased after thinning events took place. The TRIPLEX-Management model was tested against published observational data for Jack Pine (*Pinus banksiana* Lamb.) stands subjected to PCT in Northwestern Ontario, Canada. The coefficients of determination (R^2) between the predicted and observed variables including stand density, mean DBH (diameter at breast height), the quadratic mean DBH, total volume and merchantable volume as well as belowground, aboveground, and total biomass ranged from 0.50 to 0.88 ($n = 20$, $P < 0.001$) with the exception of mean tree height ($R^2 = 0.25$, $n = 20$, $P < 0.05$). Overall, the Willmott index of agreement between predicted and observed variables ranged from 0.97 to 1.00. Results show that the TRIPLEX-Management model is generally capable of simulating growth response to PCT for Jack Pine stands.

1. Introduction

Forest management practices can influence the carbon (C) balance of forests (Brown et al., 1996; Thornley and Cannell, 2000; Jandl et al., 2007), and forest thinning practices are considered an effective way in which to accelerate tree growth, reduce mortality, and increase both productivity and overall timber yield (Smith et al., 1997; Nabuurs et al., 2008). The Kyoto Protocol offered countries the option to include forest managerial activities within their participation in order to enhance sink potential into their Kyoto accounting during the first commitment period (2008–2012) (UNFCCC, 1997). Be that as it may, there is also a need to modify current managerial practices to optimize forest growth and C sequestration under conditions of climate change (Nuutinen et al., 2006; Garcia-Gonzalo et al., 2007a). A new provision requires forest resource managers to make use of forest simulation models in order to be able to make decisions that satisfy long-term strategy (Peng, 2000). Henceforth, forest models must be able to simulate key ecosystem processes regarding C, nitrogen (N), and water cycling (Mäkelä et al., 2000; Johnsen et al., 2001; Landsberg, 2003) and the effects of forest management practices (e.g., thinning) on forest growth and yield as well as C and N cycling. Therefore, it is essential to develop a process-based model with the capacity to incorporate forest management within its scope of functionality to support decision making strategies.

Regression models based on statistical relationships are the traditional growth and yield models used in forestry. However, empirical models work well as management tools for forecasting stand growth when environments only experience inconsequential change, but they should not be used for predictions under which new conditions arise such as changing climatic conditions. In contrast to empirical models, process-based models can be used as important forest management tools to explore growth and yield of forest stands to predict the effects of disturbances when environmental conditions change considerably (Mäkelä et al., 2000;

---

* Corresponding author. Tel.: +1 514 987 3000x1056.
E-mail address: peng.changhui@uqam.ca (C. Peng).

0304-3800/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2010.09.019

Johnsen et al., 2001; Peng et al., 2002; Landsberg, 2003). Since they are based on the representation of forest ecosystem processes such as photosynthesis, respiration, soil organic matter decomposition, and N cycling, they can contribute in the prediction of long-term impacts due to climate change. Several process-based models such as 3-PG (Landsberg and Waring, 1997; Landsberg et al., 2001), 4C (Lasch et al., 2005), EFIMOD (Komarov et al., 2003), FinnFor (Kellomäki and Väisänen, 1997; Matala et al., 2003), ForeSAFE (Wallman et al., 2005), PROMOD (Sands et al., 2000), TREEDYN3 (Bossel, 1996), and TRIPLEX (Peng et al., 2002) are able to predict forest growth and yield. FOREST-BGC or BIOME-BGC (Running and Gower, 1991; Running and Hunt, 1993), which were developed to simulate C and N balances, were also later modified to predict forest growth and dynamics (Korol et al., 1996; Tatarinov and Cienciala, 2006; Petritsch et al., 2007). Conceptually speaking, the goal of all these models is to provide forest yield estimates in the context of a changing environment.

In general, most ecosystem models assume fully stocked even-aged forests and are not designed to simulate forest management practices and impacts (Petritsch et al., 2007). Indeed, only a handful of studies have reported measures on how to take into consideration forest management practices using process-based models (Matala et al., 2003; Battaglia et al., 2004; Tatarinov and Cienciala, 2006; Petritsch et al., 2007; Miehle et al., 2009) while predicting the effects of climate change on forest functions such as C sequestration and timber yield (Lasch et al., 2005; Cienciala and Tatarinov, 2006; Garcia-Gonzalo et al., 2007b). These models, unfortunately, have neither been widely nor well validated by way of comparing model predictions against independent field data sets. In addition, the potential effects of thinning on growth behavior and C and N cycling have not been well presented.

For this study, model components were added into TRIPLEX1.0 (Peng et al., 2002) to incorporate thinning practices within the process-based model. The goal was to adapt TRIPLEX1.0 to be proficient in quantifying forest growth, timber yield, biomass, and C sequestration within managed forest systems. The objective of this study was to develop a new thinning submodel (TRIPLEX-Management) to quantify the effects of pre-commercial thinning (PCT) on forest growth, timber yield, biomass, and C sequestration in response to climatic conditions, utilizing Jack Pine (*Pinus banksiana* Lamb.) stands in Northwestern Ontario, Canada, to test model performance. This study hypothesized that (1) PCT may change overall diameter distribution and (2) incorporating Weibull diameter distributions into TRIPLEX1.0 will enable the newly developed TRIPLEX-Management model to capture the response of forest growth to PCT practices.

2. Methods

2.1. Model development

TRIPLEX1.0 is a process-based model that integrates three well-established models into one: 3-PG (Landsberg and Waring, 1997), TREEDYN3.0 (Bossel, 1996), and CENTURY4.0 (Parton et al., 1993). The model can simulate key C and N cycling processes such as C allocation and N mineralization by utilizing monthly mean temperatures, precipitation, and relative humidity from a given forest stand (Peng et al., 2002). This hybrid approach combines physical, biological, and biogeochemical processes that control the dynamics of C, N, and water. A unique feature of TRIPLEX1.0 is its ability to predict growth and yield of a forest stand based on ecological mechanisms and C balances (Zhou et al., 2005). TRIPLEX1.0 includes the following six submodels:

(1) Photosynthetically active radiation (PAR) (Bossel, 1996). PAR is calculated as a function of the solar constant, radiation fraction, solar height, and atmospheric absorption. Forest production and C and N dynamics are primarily driven by solar radiation.

(2) Gross primary production (GPP) (Landsberg and Waring, 1997). GPP is calculated as a function of the monthly mean air temperature, stand age, soil water content, N limitation (f_N, dimensionless), and the percentage of frost days during a period of a single month as well as the leaf area index.

(3) Net primary productivity (NPP) (Landsberg and Waring, 1997). NPP is the difference between autotrophic respiration and GPP. This is a modification from past usage where it acted as a constant of the ratio (C_{NPP}, dimensionless) of NPP to GPP (Peng et al., 2002). Autotrophic respiration (GR, t ha^{-1}) and maintenance respiration (MR, t ha^{-1}) were treated separately and governed by the nitrogen factor, air temperature (T_a, °C), and component C pools such as wood (W_w, t ha^{-1}), branches (W_{Br}, t ha^{-1}), foliage (W_f, t ha^{-1}), coarse roots (W_{cr}, t ha^{-1}), and fine roots (W_{fr}, t ha^{-1}), following the recent release of the TRIPLEX-Flux version (Zhou et al., 2008):

$$\mathrm{MR} = (0.02(W_f + W_{fr}) + 0.01(W_{Br} + W_w + W_{cr})) \times Q_{10} \tag{1}$$

$$\mathrm{GR} = \left(0.35 - \frac{f_N}{10}\right)(\mathrm{GPP} - \mathrm{MR}) \tag{2}$$

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{MR} - \mathrm{GR} \tag{3}$$

$$Q_{10} = 2.3^{0.1(T_a - 20)} \tag{4}$$

The N pool plays a substantial role as an output of the soil submodel and an input for the forest production submodel. In relation to TRIPLEX 1.0, nitrogen limitation is a function of available N (N_{avl}, t ha^{-1}), potential NPP ($\mathrm{NPP_{pot}}$, t ha^{-1}), and the C:N response ratio ($B_{C:N}$, dimensionless) of photosynthetic products that is calculated as:

$$f_N = \min\left(1.0, \frac{N_{avl} \cdot B_{C:N}}{\mathrm{NPP_{pot}}}\right) \tag{5}$$

where $\mathrm{NPP_{pot}} = \mathrm{GPP_{pot}} \times C_{NPP}$. $\mathrm{GPP_{pot}}$ (t ha^{-1}) is the maximum GPP without N limitation.

(4) Forest growth and yield submodel (FYG) (Bossel, 1996). The primary variables in FYG are the increment of tree diameter and height, calculated using a function of the stem wood biomass increment developed by Bossel (1996).

(5) Soil C and N (SCN) (Parton et al., 1993). SCN is based on the CENTURY soil decomposition submodel (Parton et al., 1993) since it provides realistic estimates of both C and N mineralization rates for Canadian boreal forest ecosystems (Peng et al., 1998). Soil C decomposition rates for each pool are calculated as functions of maximum decomposition rates, soil moisture effects, and soil temperature.

(6) Soil water submodel (SW) (Parton et al., 1993). SW is a simplified water budget module that calculates monthly water loss through transpiration and evaporation as well as through soil and snow water content following the soil water module within CENTURY (Parton et al., 1993).

A more detailed description of the features, structure, mathematical algorithms, sensitivity analysis, and development strategy of TRIPLEX1.0 have been previously reported by Peng et al. (2002) and Liu et al. (2002).

2.1.1. Incorporating diameter distribution into TRIPLEX1.0

Diameter distribution, an important factor of stand structure, was incorporated into TRIPLEX1.0. The three-parameter Weibull distribution model was used for this study to characterize diameter distribution for a given stand since it is flexible and yields probabilities with ease and without the need for numerical integration (Cao, 2004). Certain studies have indicated that the Weibull function adequately fits diameter distribution for both unmanaged and managed forest ecosystems under a variety of thinning regimes (Zarnoch et al., 1982; Álvarez González et al., 2002; Cao, 2004; Nord-Larsen and Cao, 2006). The probability distribution function of the three-parameter Weibull distribution model is described as:

$$f(D) = \left(\frac{c}{b}\right)\left(\frac{D-a}{b}\right)^{c-1} \exp\left[-\left(\frac{D-a}{b}\right)^{c}\right] \tag{6}$$

where a, b, and c are the location, scale, and shape parameters, respectively, of the Weibull distribution, and D is the DBH. The location parameter, such as the name implies, places the start location of the distribution along the abscissa. It stretches out the distribution while increasing the value of the scale parameter and holding the shape parameter constant. The shape parameter controls the behavior of the distribution.

The maximum likelihood method was used (R Development Core Team, 2009) to fit Eq. (6) for the DBH distribution of each plot, including stands that were thinned. When the initial estimate of a was negative, it was set to one-half of the minimum diameter in the plot after which the other two parameters were reestimated. At this point, the general form of a linear regression model was used to relate the Weibull function parameters to mean DBH ($\bar{D}$, cm), age (A, years), mean height ($\bar{H}$, m), and stand density (SD, trees ha^{-1}), which were then predicted by TRIPLEX1.0:

$$\hat{y} = f(\bar{D}, \bar{H}, A, \mathrm{SD}) = \theta_0 + \theta_1\bar{D} + \theta_2\bar{H} + \theta_3 A + \theta_4 \ln(\mathrm{SD}) \tag{7}$$

where $\hat{y}$ is the estimate of a specific Weibull parameter (a, b, and c), and θ_0 to θ_4 are the regression model parameters. Stepwise linear regression analysis (R Development Core Team, 2009) was applied to identify a set of candidate functional forms based on a 0.05 significance level.

2.1.2. *Forest thinning considerations*

Since the original version of TRIPLEX1.0 did not include a forest management component, forest thinning was modeled by the inclusion of thinning time (Age$_{\mathrm{T}}$, years) and thinning intensity (I_{T}, %) in the newly developed TRIPLEX-Management model. Diameter distributions were estimated before the thinning treatment took place in order to quantify basic stand characteristics of the post thinning stand for future simulations. The thinning methods "thinning from above" and "thinning from below" were designed to model forest thinning practices. The following variables were considered:

(1) Thinning intensity in relation to stand density (I_{SD}, %) was fixed as an input to the model by users or modelers. The lower (L_0, cm) and upper (U_0, cm) bounds of the DBH class for the residual stand was determined by Eqs. (8) and (9) while the lower (L, cm) and upper (U, cm) bounds of the DBH class for a given stand were determined by the formula SD × $f(D)$ > 1, which represents at least one tree in a given DBH class. The mean DBH and the quadratic mean DBH (D_{g}, cm) of the residual stands were then obtained by means of calculating the mathematical expectations of D and D^2 based on the diameter distribution function $f(D)$ by way of Eqs. (10) and (11). The definite integrals solution was a numerical approximation by which the area beneath the Weibull probability density function was determined by summing numerous inscribed rectangles. For model application, this study used $U_0 = U$ for "thinning from below" and $L_0 = L$ for "thinning from above".

$$I_{\mathrm{T}} = I_{\mathrm{SD}} = \frac{N_{\mathrm{Removed}}}{N_{\mathrm{Before}}} \tag{8}$$

$$N_{\mathrm{Removed}} = N_{\mathrm{Before}}\left\{1 - \exp\left[-\left(\frac{L_0-a}{b}\right)^{c}\right] + \exp\left[-\left(\frac{U_0-a}{b}\right)^{c}\right]\right\} \tag{9}$$

$$\bar{D} = E(D) = \int_{L_0}^{U_0} D \cdot f(D)dD \tag{10}$$

$$D_{\mathrm{g}}^2 = E(D^2) = \int_{L_0}^{U_0} D^2 \cdot f(D)dD \tag{11}$$

where N_{Residual} and N_{before} are the number of residual trees and the number of trees, respectively, before thinning treatment takes place. Tree height (H, m) for each DBH class was estimated by the height-diameter equation (Eq. (12)) for boreal Jack Pine forests developed by Zhang et al. (2002). Mean height was then calculated following Eq. (13).

$$H = 1.3 + 23.9313 \times (1 - e^{-0.0812 \cdot D})^{1.7149} \tag{12}$$

$$\bar{H} = \int_{L_0}^{U_0} Hf(D)dD \tag{13}$$

(2) Thinning intensity in relation to basal area (I_{Ba}, %) determines the ratio of the basal area to be removed (B_{Removed}, m^2 ha^{-1}) to the basal area before thinning treatment takes place (B_{Before}, m^2 ha^{-1}):

$$I_{\mathrm{T}} = I_{\mathrm{Ba}} = \frac{B_{\mathrm{Removed}}}{B_{\mathrm{Before}}} \tag{14}$$

The lower and upper bounds of residual stands were then computed according to Eqs. (15) and (16). They were used to calculate mean DBH, mean height, and the mean quadratic DBH of the residual stands through Eqs. (10)–(13).

$$B_{\mathrm{Before}} = \frac{\pi}{4}\mathrm{SD}\int_{L}^{U} D^2 f(D)dD \tag{15}$$

$$B_{\mathrm{Removed}} = B_{\mathrm{Before}} - \frac{\pi}{4}\mathrm{SD}\int_{L_0}^{U_0} D^2 f(D)dD \tag{16}$$

(3) Thinning intensity in relation to volume (I_{V}, %) is another alternative way in which to describe thinning intensity. This variable represents the relative volume removal (V_{Removed}, m^3 ha^{-1}). Volume before thinning (V_{Before}, m^3 ha^{-1}) was calculated from stand density, tree form (φ) (Eq. (20)), and tree height for a given DBH and the Weibull function ($f(D)$) as follows:

$$I_{\mathrm{T}} = I_{\mathrm{V}} = \frac{V_{\mathrm{Removed}}}{V_{\mathrm{Before}}} \tag{17}$$

$$V_{\mathrm{Before}} = \frac{\pi}{4}\mathrm{SD}\int_{L}^{U} H\varphi D^2 f(D)dD \tag{18}$$

$$V_{\mathrm{Removed}} = V_{\mathrm{Before}} - \frac{\pi}{4}\mathrm{SD}\int_{L_0}^{U_0} H\varphi D^2 f(D)dD \tag{19}$$

$$\varphi = 0.52 - 0.002 \cdot \left(\frac{H}{D} - 90\right) \tag{20}$$

For PCT treatments, the most important step was to obtain the lower boundary (thinning threshold) and upper boundary ($U_0 = U$) of the residual stands for all three calculation approaches.

2.1.3. Modifications made to the original model source code

Certain variables were recalculated for purposes of simulation. This was necessary due to the model mechanism advancement to the next time step when forest thinning occurs. Other model variables or processes that were identified as phenomenon in which full understanding remains incomplete such as tree mortality and increased litterfall due to thinning slash cannot be auto-updated. Certain necessary changes were consequently made to these related processes.

2.1.3.1. Modification in the FYG submodel. Tree mortality is separated into mortality with and without competition in TRIPLEX1.0 (Peng et al., 2002). Both mortality scenarios are simply set as constant values. Given that PCT removes the majority of unhealthy trees and increases the vigor of residual stems, the mortality without competition scenario has been empirically reduced after thinning in the TRIPLEX-Management version.

Total stand volume (V_T, m^3 ha^{-1}) was estimated as a function of mean DBH, mean height, stand density, and tree form by Eq. (21) in the original TRIPLEX1.0 model. A tendency to always underestimate tree volume for young stands seems to afflict TRIPLEX1.0 (Peng et al., 2002). In the current version, stand volume is the sum of all tree volume for all DBH classes (Eq. (22)). Merchantable volume (V_M, m^3 ha^{-1}) was calculated as the sum of individual trees for all trees greater than 9 cm in DBH (Eq. (23)).

$$V = \mathrm{SD} \times \frac{\pi}{4}\varphi\bar{D}^2\bar{H} \tag{21}$$

$$V_T = \frac{\pi}{4}\mathrm{SD}\int_L^U H\varphi D^2 f(D)dD \tag{22}$$

$$V_M = \frac{\pi}{4}\mathrm{SD}\int_9^U H\varphi D^2 f(D)dD \tag{23}$$

2.1.3.2. Modification in the SCN submodel. PCT is generally carried out only in even-aged forests that are approximately 15 years old. In many such forest stands, trees that are selected for removal are often too small for heavy machinery usage. The soil environment, therefore, is hardly affected by this type of thinning operation. Several studies have reported that prescribed thinning has a negligible effect on soil respiration (Vesala et al., 2005; Campbell et al., 2009). It was consequently assumed in the current study that thinning treatments have little effect on soil processes such as soil respiration. Nevertheless, it is assumed that thinning slash is always left on site to enrich the soil. Litterfall pools in the SCN submodel were therefore increased by means of thinning intensity.

To quantify the biomass of residual stands and the slash that has entered into soil, biomass equations were used to estimate the change rate before and after thinning treatments occurred. The Jack Pine biomass equations used in this study were reported by Lambert et al. (2005) for aboveground biomass (Eq. (24) and Li et al. (2003) for belowground biomass (Eq. (25)).

Table 1
Jack Pine biomass equation parameters from Lambert et al. (2005).

Component	β_1	β_2	β_3
Wood	0.0199	1.6883	1.2456
Bark	0.0141	1.5994	0.5979
Branches	0.0185	3.0584	−0.9816
Foliage	0.0325	1.7879	-

Note: β_1, β_2, and β_3 are the parameters used in the biomass equation of $\mathrm{Biomass}_i = \beta_1 D^{\beta_2} H^{\beta_3}$.

$$\mathrm{Biomass}_i = \beta_1 D^{\beta_2} H^{\beta_3} \tag{24}$$

$$\mathrm{RB} = 0.222 \cdot \mathrm{AB} \tag{25}$$

where $\mathrm{Biomass}_i$ is the dry biomass compartment i of a living tree (kg) in which i represents wood, bark, branches, and foliage; β_1 to β_3 are the parameters of the biomass equation (Table 1); and RB and AB are root and aboveground biomass, respectively, obtained by adding their corresponding compartments. Biomass change rates ($I_{B,i}$, %) for each biomass component i of a stand were estimated as the ratio of the summed biomass in each DBH class for the before thinning and after thinning stand (Eq. (26)). Therefore, the increments of the litterfall pools ($\Delta\mathrm{Litter}_i$, kg) were calculated by the product of the original stand C pools (TRIPLEX-Management) before thinning ($W_{\mathrm{Before},i}$, kg ha^{-1}) and the change rates due to thinning (Eq. (27)). Furthermore, the residual stand C pools ($W_{\mathrm{Residual},i}$, kg ha^{-1}) were obtained by way of the differences in stand C pools before thinning and the increments of litterfall pools (Eq. (28)). All calculations in relation to root biomass (e.g., root litterfall) are based on Eq. (25).

$$I_{B,i} = 1 - \frac{\int_{L_0}^{U_0} \mathrm{Biomass}_i f(D)dD}{\int_L^U \mathrm{Biomass}_i f(D)dD} \tag{26}$$

$$\Delta\mathrm{Litter}_i = W_{\mathrm{Before},i} I_{B,i} \tag{27}$$

$$W_{\mathrm{Residual},i} = W_{\mathrm{Before},i}(1 - I_{B,i}) \tag{28}$$

2.2. Sites

PCT may have a positive effect on individual tree volume growth for Jack Pine stands (e.g., Bella and DeFranceschi, 1974; Groot et al., 1984), which in itself may lead to a shorter rotational time period (Morris et al., 1994). Published Jack Pine forest PCT data (Tong et al., 2005) in Northwestern Ontario was used in this study to validate the modified model. Beginning in the 1980s or even earlier, PCT treatments were applied a single time to selected stands

Table 2
Site information based on a study by Tong et al. (2005).

Site	Stand	Age (year)	Age$_T$ (year)	I_T (%)	SD (trees ha^{-1})		DBH (cm)		Tree height (m)		V_T (m^3 ha^{-1})		V_M (m^3 ha^{-1})	
					Control	PCT	Control	PCT	Control	PCT	Control	PCT	Control	PCT
1	Furniss road	36	14	43	4080	2340	9.1 (3.15)	11.1 (4.90)	9.8 (3.38)	10.2 (4.46)	161.6	163.1	117.5	143.4
2	Reba road	36	15	36	2700	1720	10.9 (3.82)	13.5 (4.07)	10.1 (3.83)	13.3 (3.48)	159.1	176.7	133.2	161.0
3	Encamp	26	12	44	2840	1580	9.3 (5.35)	11.9 (4.56)	8.1 (4.00)	9.4 (3.44)	144.2	104.3	121.4	93.5
4	Mack 1	26	13	62	5740	2180	7.8 (2.74)	10.9 (2.52)	8.5 (3.29)	10.2 (1.94)	150.6	107.7	90.5	85.0
5	Mack 5	26	13	23	5260	4040	8.2 (3.08)	8.9 (3.31)	10.3 (2.27)	9.9 (2.54)	167.1	145.8	104.4	100.0
6	Graham road	34	5	21	2800	2220	11.9 (2.97)	13.7 (3.56)	14.3 (1.84)	14.3 (2.58)	222.9	235.3	188.0	213.3
7	Nelson Lake	31	11	25	2200	1640	11.9 (3.88)	13.0 (2.61)	9.0 (1.65)	9.6 (1.58)	126.1	107.5	107.6	95.0
8	Mack 2	26	12	68	4260	1360	8.4 (2.61)	14.1 (3.08)	9.3 (1.50)	11.3 (1.69)	122.1	121.0	110.5	71.6
9	Mack 3	26	12	63	5820	2180	7.8 (2.36)	11.2 (2.14)	9.8 (1.30)	10.3 (0.99)	146.8	112.7	90.0	72.0
10	Mack 4	26	12	65	4940	1740	8.5 (2.85)	12.3 (2.12)	10.1 (1.70)	10.3 (1.07)	160.5	106.0	98.9	91.0

Note: Age$_T$ is thinning age; I_T is thinning intensity; SD is stand density; and V_T and V_M are stand volume and merchantable volume, respectively. Standard deviations are in parentheses.

Table 3
Parameters used within model simulations.

Parameter	Description	Note
PAR		
Absorb = 0.15	Atmospheric absorption factor	[a]
Cloud = 0.4	Time faction of cloudy days	[a]
PAR factor = 0.47	Solar radiation fraction	[a]
GPP		
BlCond = 0.2	Canopy boundary layer conductance (ml m^{-2} s^{-1})	[b]
MaxCond = 0.02	Max canopy conductance (ml m^{-2} s^{-1})	[b]
StomCond = 0.006	Stomata conductance (ml m^{-2} s^{-1})	[b]
ExtCoef = 0.5	Radiation extinction coefficient	[b]
TaMin = 5	Min. temperature for growth (°C)	[a]
TaMax = 30	Max. temperature for growth (°C)	[a]
Topt = 15	Optimum temperature for growth (°C)	[c]
N factor = 0.2	N factor for tree growth	[d]
Na = 3	Effects of age to GPP	[e]
Sla = 6	Specific leaf area (m^2 kg^{-1})	[c]
NPP		
GamaF = 0.01	Leaf turnover per year	[f]
GamaR = 0.21	Fine root turnover per year	[g]
$B_{C:N}$ = 24.5	C:N response ratio	[h]
C_{NPP} = 0.39	A constant ratio of NPP/GPP	[i]
Soil C and N		
Lnr = 0.26	Lignin–N ratio	[d]
Ls = 0.215, 0.215, 0.235, 0.255, 0.255	Lignin for leaf, fine root, coarse root, branch, and wood	[d]
Soil water		
A1, A2, A3 = 15, 15, 15	Soil water depth of layer 1, 2, and 3 (cm)	[d]
AWL1, 2, and 3 = 0.5, 0.3, 0.2	Relative root density for layer 1, 2, and 3	[d]
KF = 0.5	Fraction of H_2O flow to stream	[f]
KD = 0.5	Fraction of H_2O flow to deep storage	[f]
KX = 0.3	Fraction of deep storage water to stream	[f]
AWater = 250	Max. soil water (mm)	[f]
Growth and yield		
MiuNorm = 0.006 (0.005[k])	Normal mortality	This study
MiuCrowd = 0.02	Competition mortality	[f]
Species parameter		
CSP = 0.22	Wood C density (t C m^{-3})	[j]
CD = 25	Crown to stem diameter ratio	[a]
AlphaC = 0.05	Canopy quantum efficiency	[a]
MaxHeight = 25	Max. height (m)	This study
AgeMax = 150	Max. stand age (year)	This study

[a] Bossel (1996).
[b] Coops et al. (2001).
[c] Kimball et al. (1997).
[d] Values are provided by CENTURY (Parton et al., 1993).
[e] Landsberg and Waring (1997).
[f] Zhou et al. (2005).
[g] Steele et al. (1997).
[h] Liu and Greaver (2009).
[i] Ryan et al. (1997).
[j] Newcomer et al. (2000).
[k] Residual stand value after PCT treatment has taken place.

by way of the practice of low thinning using brush saws. Dominant Jack Pine stands were measured in 2003 (Table 2) where the total volume and merchantable volume were estimated by summing the volumes of each segment between two cross sections as reported by Tong et al. (2005). A total of 10 sites containing both PCT and control stands represented the different groups of thinning intensity and thinning age. The site index was from 18 m to 20 m (the dominant height after a 50 year period of growth). At each site, 10 plots comprising of 0.01 ha each were established, five of which were control stands and five of which were PCT stands. These sites were naturally regenerated or seeded throughout a period from 1967 to 1977. The thinning time (Age_T, year) ranged from 5 to 15 years, and the thinning intensity in relation to stand density ranged from 21% to 68% of tree removal (Table 2).

Monthly air temperature, precipitation, and relative humidity were obtained from the IPCC 20th Century experiment applying the third version of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM3.1) for the years 1850–2000 (http://www.cccma.ec.gc.ca). The average value of four corresponding grids for Northwestern Ontario was used in this study.

2.3. *Simulation experiments*

2.3.1. *Parameterization and initialization*

The TRIPLEX1.0 model operates with the following sets of input data and parameters (Table 3):

1. An ecophysiological parameter file that characterizes the necessary eco-parameters.
2. A stand initialization file including species, regenerated year, latitude, site class, initial soil C, stocking, thinning time, and thinning intensity.
3. A form that describes species parameters such as wood C density and maximum height.
4. A climate data file exhibiting monthly temperature, precipitation, and relative humidity.

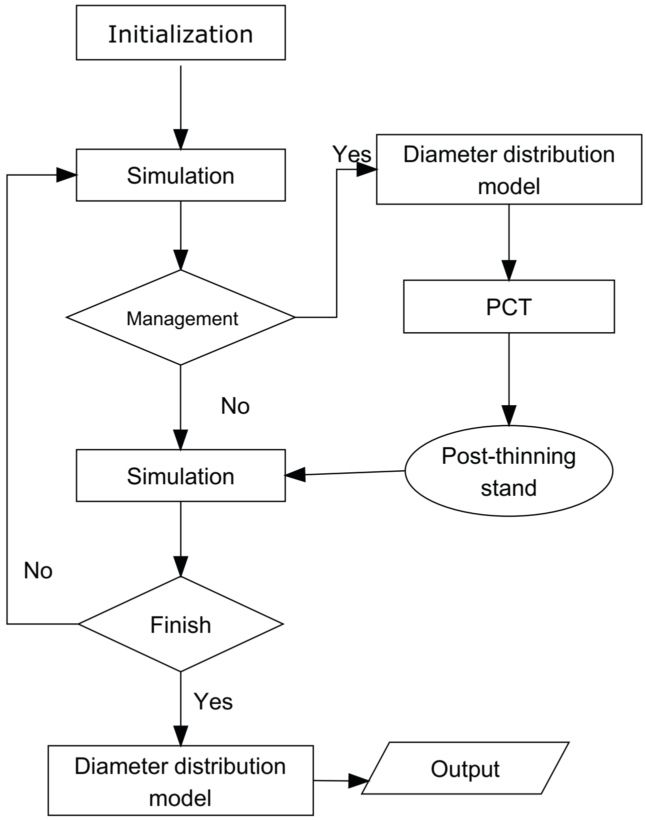

Fig. 1. Flow diagram of a simulation run. PCT refers to pre-commercial thinning.

The TRIPLEX1.0 model has been parameterized for pure Jack Pine stands (Peng et al., 2002) in Ontario as well as Jack Pine, Black Spruce (*Picea mariana* (Mill.) BSP), and Trembling Aspen (*Populus tremuloides* Michx) mixed stands in central Canada and northeastern Ontario (Zhou et al., 2004, 2005). It has also been parameterized for subtropical forest regions in southeastern China (Zhang et al., 2008) and boreal and temperate forest ecosystems in northeastern China (Peng et al., 2009). It is noteworthy that none of the previous studies mentioned considered the potential impacts of thinning on forest growth and yield.

2.3.2. Simulation runs

The scheme of the simulation runs is provided in Fig. 1. First of all, simulations began at the point of yearly regeneration for each stand. Next, if thinning occurs, the diameter distribution model parameters were estimated from the last month of the year before thinning. Residual stand characteristics (mean DBH, mean height, and stand density) were calculated and reentered as an input for the next time step in relation to the thinning intensity defined by the user. The biomass of leaf, wood, branch, and fine and coarse roots was reduced along with the change rates obtained from the biomass equations and the diameter distribution model. The model continued to simulate forest growth, C, and N dynamics for the residual stand until simulations concluded. Lastly, variables of interest such as DBH, volume, and biomass were output.

2.3.3. Model evaluation

The one-sample Kolmogorov–Smirnov (K–S) test (R Development Core Team, 2009) was used to evaluate the performance of the diameter distribution model. The statistical value of the K–S test within a plot is the largest absolute difference between the hypothesized distribution and the observed distribution from that plot. The smaller the statistical value the better the fit. The mean absolute error (MAE%, Eq. (29)) and the root mean square error (RMSE%, Eq. (30)) were used to evaluate the differences in the predicted and observed data.

$$\mathrm{MAE\%} = 100\frac{\sum_{i=1}^{n}|P_i - O_i|}{n\bar{O}} \tag{29}$$

$$\mathrm{RMSE\%} = 100(\bar{O})^{-1}\left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \tag{30}$$

where P is the predicated value and O is the observed value; $\bar{O}$ and $\bar{P}$ are the mean of the observed and predicted values, respectively; n is the number of observations.

Three criteria were calculated to evaluate the performance of the TRIPLEX-Management model. A linear regression between the observed and predicted values was used to evaluate model performance. The hypothesis is that the regression passes through the origin and has a slope of unity (45°). MAE% and RMSE% were also used to evaluate prediction errors of the TRIPLEX-Management model. The Willmott index of agreement (d) (Willmott, 1982) is an indicator of model performance. It carries a value from 0 to 1.0, and is expressed as:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i| + |O_i|)^2}\right] \tag{31}$$

where the index of 1.0 indicates perfect agreement (Willmott, 1982).

2.3.4. Sensitivity analysis

Sensitivity analysis was carried out in order to investigate the effects of the newly introduced diameter distribution parameters and input variables for the PCT regime on forest C dynamics in the TRIPLEX-Management model. Sensitivity scenarios involved applying a 10% increase or decrease in Weibull distribution parameters (a, b, and c), mortality without competition in residual stands, and thinning intensity. Moreover, a two year advance or extension in thinning time was also considered within the sensitivity scenarios. The model was run repeatedly under these scenarios, after which the results were compared to previous runs.

3. Results

3.1. Diameter distribution comparison

Table 4 provides the parameter prediction equation systems of Weibull diameter distribution within the TRIPLEX-Management model. The scale parameter had the highest R^2 (0.83) value and the lowest MAE% (9.0%) and RMSE% (13.2%) values among the three Weibull parameters while the location parameter and the shape parameter had low R^2 values and high MAE% and RMSE% values (Table 4). The mean and standard variations of the K–S test goodness of fit for the entire data set were 0.19 and 0.09, indicating that the diameter distribution model performs well overall.

Fig. 2 shows that the simulated diameter distribution carried out by TRIPLEX-Management derived from stand characteristics agreed well with observed Jack Pine stand diameter distributions. PCT altered stand diameter distribution. The location parameter of the Weibull distribution within the PCT stands was larger than in the control stands (Fig. 2C and F) given that the PCT treatments removed lower diameter class trees. Furthermore, diameter distributions within the PCT stands were wider than in the control stands (Fig. 2C and F), and diameter distributions in the PCT stands were more negatively skewed than in the control stands (Fig. 2C and F).

Table 4
Eq. (7) estimated coefficients and their statistics using stepwise linear regression analysis (R Development Core Team, 2009) for Jack Pine stands.

$\hat{y}$	Slope coefficient					Model statistics		
	Intercept	$\bar{D}$	$\bar{H}$	A	SD	R^2	MAE%	RMSE%
a	−1.149	0.471		−0.045		0.354	32.7	51.7
b	1.621	0.586		0.050		0.825	9.0	14.2
c	1.269	0.259		−0.023		0.192	21.5	34.6

Notes: $\hat{y}$ is the dependent variable in Eq. (7) $(\hat{y} = f(\bar{D}\bar{H}, A, \ln(\text{SD})) = \theta_0 + \theta_1\bar{D} + \theta_1\bar{H} + \theta_3 A + \theta_4 \ln(\text{SD}))$; *a*, *b*, and *c* are the estimated location, scale, and shape parameters of the three-parameter Weibull distributions, respectively; $\bar{D}$ is mean diameter at breast height; $\bar{H}$ is mean tree height; *A* is stand age; SD is stand density; MAE% is the mean absolute error; and RMSE% is the root mean square error.

3.2. *Stand characteristic comparison*

Scatter plot results of the comparisons made between the simulated and observed data in relation to stand characteristics are provided in Fig. 3 and Table 5. The predicted and observed data pairs were close to the 1:1 line (Fig. 3), although a general trend in underestimation occurred (Table 5). The coefficient of determination (R^2) for all stand characteristics ranged from 0.57 to 0.88 except for mean height (R^2 = 0.25) (Table 5), and the MAE% ranged from 7.3% to 16.0% for all stand variables. The RMSE% for all forest stand variables ranged from 9.4% to 20.8%. The Willmott index of agreement between the observed and simulated basic stand variables ranged from 0.99 to 1.00. Statistical analysis (Table 5) confirmed that TRIPLEX-Management predicted stand variables reasonably well.

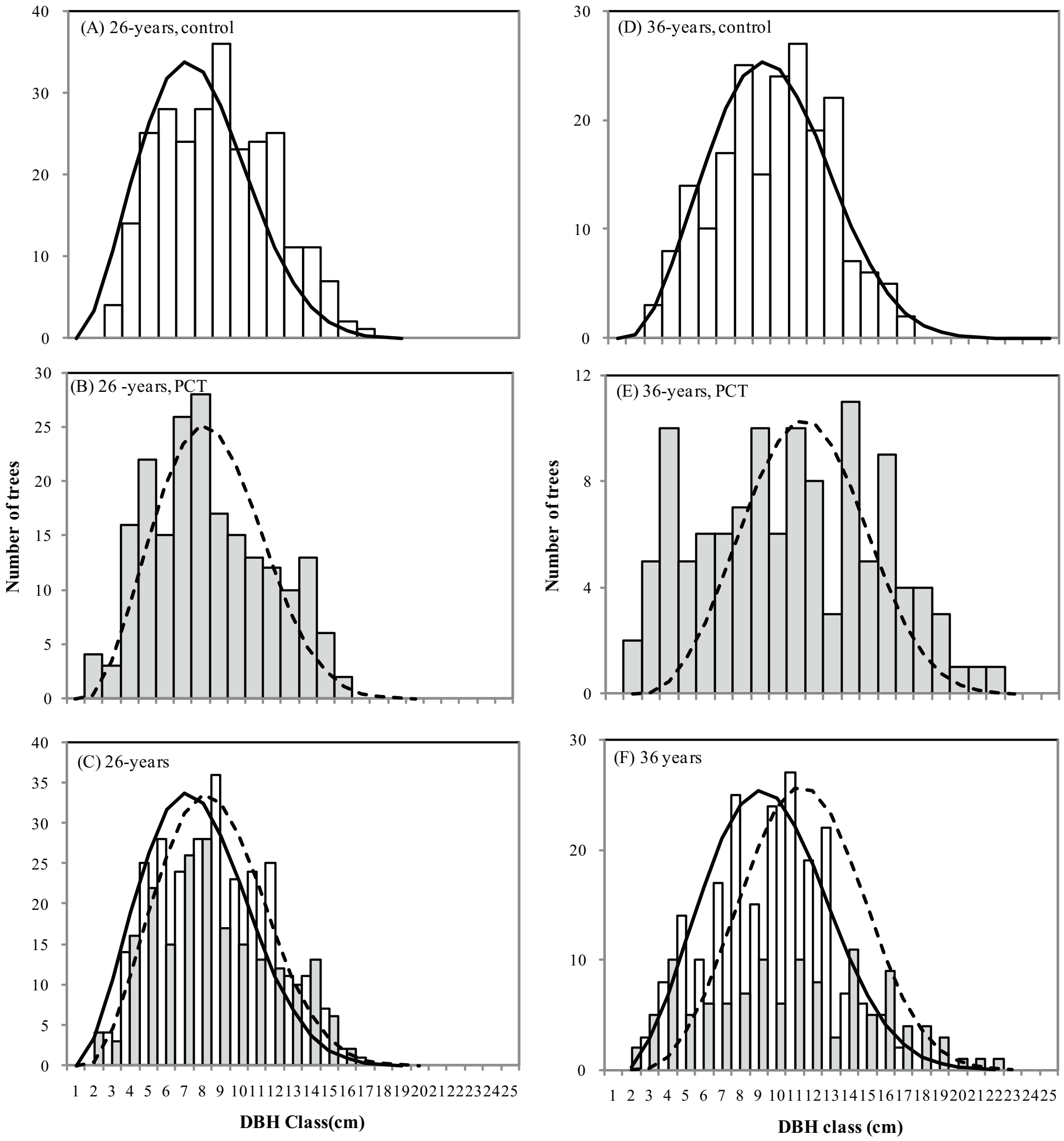

Fig. 2. Comparison between simulated and observed diameter distributions for both unmanaged (control) and managed (PCT) Jack Pine stands of different stand ages (site 1: age = 36 years, PCT age = 14; site 5: age = 26 years, PCT age = 13) in Northwestern Ontario, Canada. Solid and dash curves represent model simulated DBH distributions of the control and PCT stands, respectively. Hollow and gray histograms represent the observed diameter distributions of the control and PCT stands, respectively.

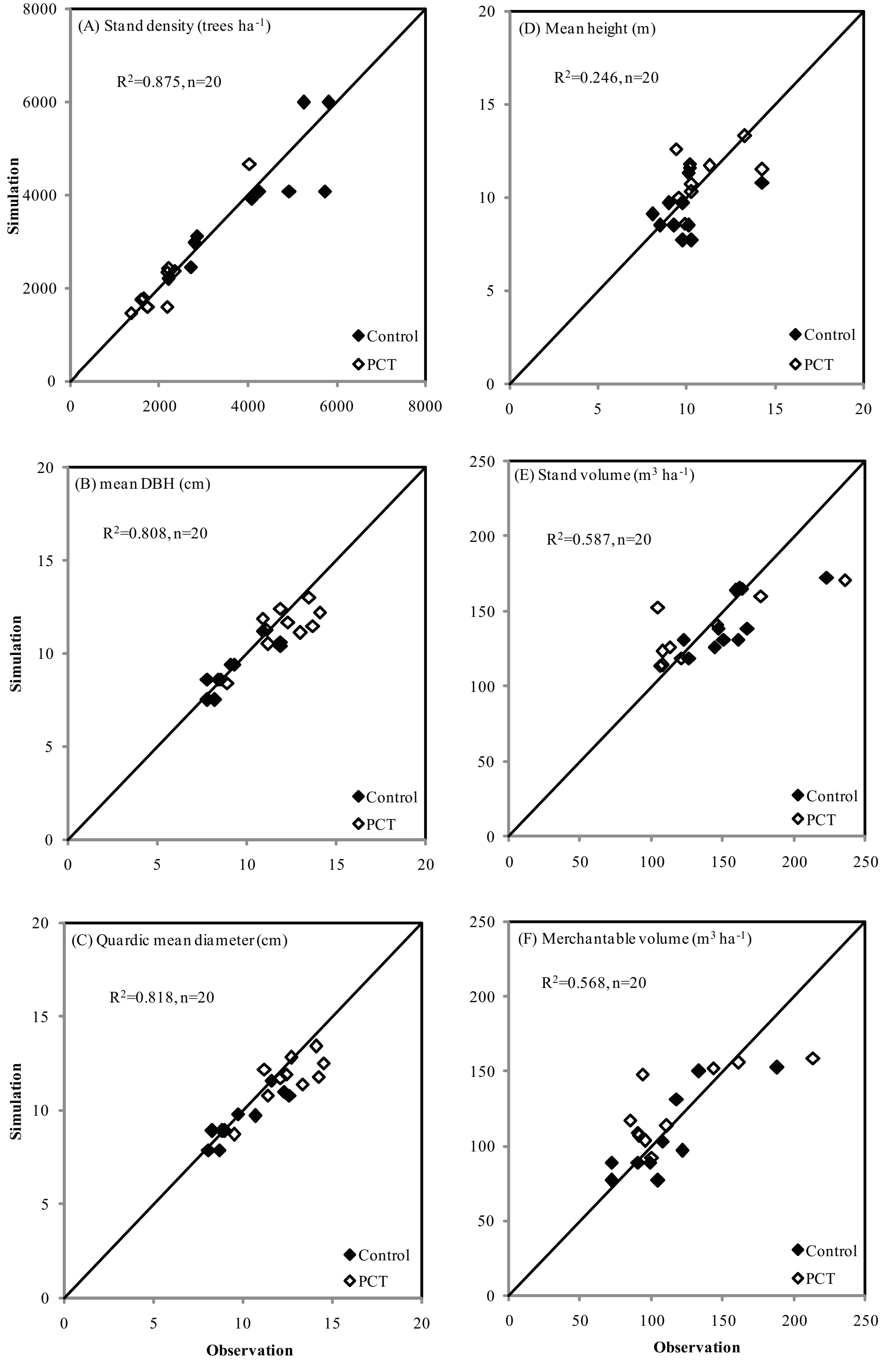

Fig. 3. Scatter plot comparisons between simulated and observed (A) stand density (trees ha^{-1}), (B) diameter at breast height (DBH) (cm), (C) quadratic mean diameter (cm), (D) mean tree height (m), (E) total stand volume (m^3 ha^{-1}), and (F) merchantable volume (DBH > 9 cm) (m^3 ha^{-1}) for 20 Jack Pine stands located within 10 sites in Northwestern Ontario (Table 2). Solid diamonds represent control plots while hollow diamonds represent PCT plots. The solid diagonal representational line is the 1:1 line.

Table 5
TRIPLEX-Management model performance.

Variable	Regression analysis			MAE%	RMSE%	d[a]
	R^2	Slope	Intercept			
Stand density (trees ha^{-1})	0.88[***]	0.90	234.47	11.0	16.6	0.99
Mean DBH (cm)	0.81[***]	0.73	2.51	7.3	9.4	1.00
Quadratic mean DBH (cm)	0.82[***]	0.74	2.35	7.3	9.6	1.00
Mean height (m)	0.25[*]	0.48	5.19	12.1	15.8	0.99
Total volume (m^3 ha^{-1})	0.59[***]	0.42	78.14	12.3	17.0	0.99
Merchantable volume (m^3 ha^{-1})	0.57[***]	0.57	50.24	16.0	20.8	0.99
Belowground biomass (t ha^{-1})	0.54[***]	0.55	4.65	21.7	25.1	0.98
Aboveground biomass (t ha^{-1})	0.50[***]	0.45	22.73	26.8	31.8	0.97
Total biomass (t ha^{-1})	0.51[***]	0.47	27.37	25.9	30.5	0.97

MAE% is the mean absolute error and RMSE% is the root mean square error.
[*] Significant at probability levels of 0.05.
[***] Significant at probability levels of 0.001.
[a] Willmott index.

Comparison results for the most essential direct measurements in forest inventory such as stand density, mean DBH, and the quadratic mean DBH showed good agreement overall (Fig. 3A–C). Regression of the predicted versus observed stand density resulted in a high R^2 of 0.88 with a slope of 0.90 and an intercept of 234 tree ha^{-1} ($n = 20$, $P < 0.001$). The MAE%, RMSE%, and Willmott index were 11.0%, 16.6%, and 0.99, respectively. Model performance in relation to mean DBH and the quadratic mean DBH was similar to model performance of stand density (Table 5).

In general, predicted and observed mean tree height data pairs were close to the 1:1 line (Fig. 3D). Regression of the computed versus observed mean tree height resulted in a low R^2 of 0.25 with a slope of 0.48 and an intercept of 5.19 m ($n = 20$, $P < 0.05$). The MAE%, RMSE%, and Willmott index were 12.1%, 15.8%, and 0.99, respectively. It is likely that such a low R^2 resulted from a wide range of H/D (30-285) in the natural forests under investigation and a relatively narrow mean height (8.1–14.3 m).

Overall agreements for total volume (Fig. 3E) and merchantable volume (Fig. 3F) were also generally acceptable. Regression of the computed versus observed total volume resulted in a relatively low R^2 of 0.59 with a slope of 0.42 and an intercept of 78.14 m^3 ha^{-1} ($n = 20$, $P < 0.001$). The MAE%, RMSE%, and Willmott index were 12.3%, 17.0%, and 0.99, respectively. Regression performance for the merchantable volume was similar. Such a low R^2 is partly attributable to the limited field data available such as an overall narrow age range from 26 to 36 years as well as the general tree volume calculation formula (Eqs. (24) and (25)) used for all tree species. Considerable prediction errors (relative error >25%, Table S1) in relation to total volume and merchantable volume predictions were found for the PCT stands of site 6 (SD = 2220 trees ha^{-1}, age = 34 years, see Table 2) where observed total volume (235.3 m^3 ha^{-1}) and merchantable volume (213.3 m^3 ha^{-1}) were much higher compared to the PCT stands of site 2 ($V_M = 161.0$ m^3 ha^{-1}, see Table 2), exhibiting similar stands age (36 years) but lower stand density (1720 trees ha^{-1}). They were even higher than those provided in site class 1 of the normal yield table developed for four primary northern Ontario tree species in the 1970s (Plonski, 1974). Similar prediction errors (relative error >20%, Table S2) were found in the control stands of site 6. These results indicate that the model underestimated tree production for stands located within site classes that exhibited reasonably good conditions.

Table 6
Predicted sensitivity of the newly introduced key variables to changes in the thinning regime for three selected Jack Pine stands (the values are the percentage change).

Jack Pine	I_T		Age_T		Mortality after PCT		a		b		c	
	+10%	−10%	+2	−2	+10%	−10%	+10%	−10%	+10%	−10%	+10%	−10%
Site 1 ($Age_T = 14$, $I_T = 43\%$)												
$\bar{D}$	7.1	−1.8	4.4	0.9	0.0	0.0	0.0	0.0	6.2	0.0	6.2	0.9
$\bar{H}$	10.3	−0.9	8.6	1.7	−0.9	0.0	0.0	0.0	9.5	0.0	9.5	0.9
V_T	4.9	−0.4	6.1	0.4	−1.8	1.1	6.4	−5.3	31.5	−22.0	4.0	1.2
V_M	8.5	−0.8	8.6	0.9	−2.0	1.1	7.7	−6.4	38.3	−26.6	7.5	1.1
Total biomass	−4.2	−1.2	−1.9	−1.8	−1.5	1.2	0.6	0.7	−3.8	−0.6	−5.5	−1.9
Soil C	−3.4	−1.6	−3.2	−1.1	−1.3	−1.5	−1.5	−1.5	−3.4	−1.5	−2.8	−1.4
Site 5 ($Age_T = 13$, $I_T = 23\%$)												
$\bar{D}$	0.1	−1.2	4.8	0.0	0.0	0.0	0.0	0.0	1.2	−1.2	−1.2	1.2
$\bar{H}$	0.1	0.0	8.1	0.0	0.0	0.0	0.0	0.0	1.2	−1.2	−1.2	1.2
V_T	−1.2	0.9	7.4	−1.4	−0.6	0.4	4.6	−4.7	27.8	−24.3	−4.0	4.3
V_M	−0.2	−0.2	16.0	−1.1	−0.7	0.2	7.4	−7.4	49.6	−41.4	−9.4	11.1
Total biomass	−0.1	−0.1	−5.5	−4.3	0.4	0.3	0.0	0.0	−0.9	−0.1	0.3	−1.2
Soil C	0.3	0.1	−0.7	0.0	0.0	0.0	0.0	0.0	−0.1	−0.1	0.0	−0.1
Site 10 ($Age_T = 12$, $I_T = 65\%$)												
$\bar{D}$	5.1	−3.4	0.9	0.0	0.0	0.0	0.0	0.0	0.9	0.0	−0.9	4.3
$\bar{H}$	7.5	0.0	6.5	1.9	0.0	0.0	0.0	0.0	6.5	1.9	−0.9	12.1
V_T	−4.4	5.9	3.9	0.2	1.5	0.4	7.2	−6.7	29.1	−20.1	−0.1	8.5
V_M	−2.1	3.6	4.6	0.2	1.4	0.4	8.5	−8.2	33.5	−24.0	0.2	10.4
Total biomass	−20.6	−0.5	−13.1	−9.2	1.3	0.5	0.1	−0.1	−16.5	−4.5	1.6	−28.9
Soil C	−1.0	0.1	−0.4	−0.3	0.0	0.0	0.0	0.0	−0.6	−0.1	−0.1	−0.7

Notes: Age_T is the thinning age; I_T is the thinning intensity; $\bar{D}$ is the mean diameter at breast height; $\bar{H}$ is the mean tree height; V_T and V_M represent total volume and merchantable volume, respectively; *a*, *b*, and *c* are the location, scale, and shape parameters of the three-parameter Weibull distributions, respectively.

3.3. Stand biomass comparison

A comparison of biomass simulations for the distribution (above and belowground) of dry matter within the model relative to biomass equation estimates is provided in Fig. 4. In general, predicted and observed biomass data pairs were close to the 1:1 line, although the model underestimated biomass production (Fig. 4). Regression of predicted versus observed total biomass resulted in a relatively low R^2 of 0.51 with a slope of 0.47 and an intercept of 27.37 t ha^{-1} ($n = 20$, $P < 0.001$, Table 5). The MAE%, RMSE%, and Willmott index were 25.9%, 30.5%, and 0.97, respectively (Table 5). Regressions for above and belowground biomass were similar. TRIPLEX-Management captured the growth response to PCT treatment while a systematic negative bias was detected in the biomass simulation, especially for sites in which reasonably good conditions existed (e.g., site 6, see Table 2). Similar results were obtained for volume estimates. However, this study recognizes that it is possible that a bias can be produced when applying this type of national scale biomass equation (Lambert et al., 2005) to a given local scale forest stand. Nevertheless, statistical analysis (Table 5) confirmed that TRIPLEX-Management still produces an overall acceptable agreement to biomass estimates generated from national biomass equations.

3.4. Sensitivity to PCT treatment

A positive relationship was found in relation to changes in thinning intensity. For example, a 10% increase in I_T resulted in increases from 0.1% to 7.1% and from 0.1% to 7.5% for mean DBH and mean height, respectively (Table 6). No significant positive or negative relationships were found for total volume and merchantable volume to thinning intensity. Similarly, no significant relationships were found between variables under consideration with a two year advance or extension of thinning age and mortality adaptation for residual stands.

The three parameters of the Weibull diameter distributions had remarkably affected basic stand characteristics and total biomass, but had no significant affect on soil C for this model (Table 6). An apparent positive response of total volume and merchantable volume was found for location parameter (a) and scale parameter (b), especially concerning the latter. A 10% increase in the scale parameter resulted in an increase from 27.8% to 31.5% and from 33.55 to 49.6% for total volume and merchantable volume, respectively (Table 6), suggesting that the accurate estimation of scale parameters of the Weibull diameter distribution is critical in predicting total volume and merchantable volume. However, the shape parameter may not follow regular patterns for all related variables.

4. Discussion

4.1. Thinning routines

This study revealed the applicability of the model with regard to forest thinning simulations. TRIPLEX-Management provides multiple ways in which to quantify thinning intensity (e.g., I_{SD}, I_{Ba}, and I_V) applying thinning methods such as “thinning from below” and “thinning from above” to calculate effects of thinning on forest growth, timber yield, biomass, and C and N dynamics. The consideration of forest management within biogeochemical-mechanistic modeling is important since it extends the applicability of the model from unmanaged to managed forests (Petritsch et al., 2007). Moreover, forest models should provide the information required for ecosystem management, forest certification, and sustainable management (Landsberg, 2003). The model is capable of simulating key variables related to thinning such as mean DBH, mean

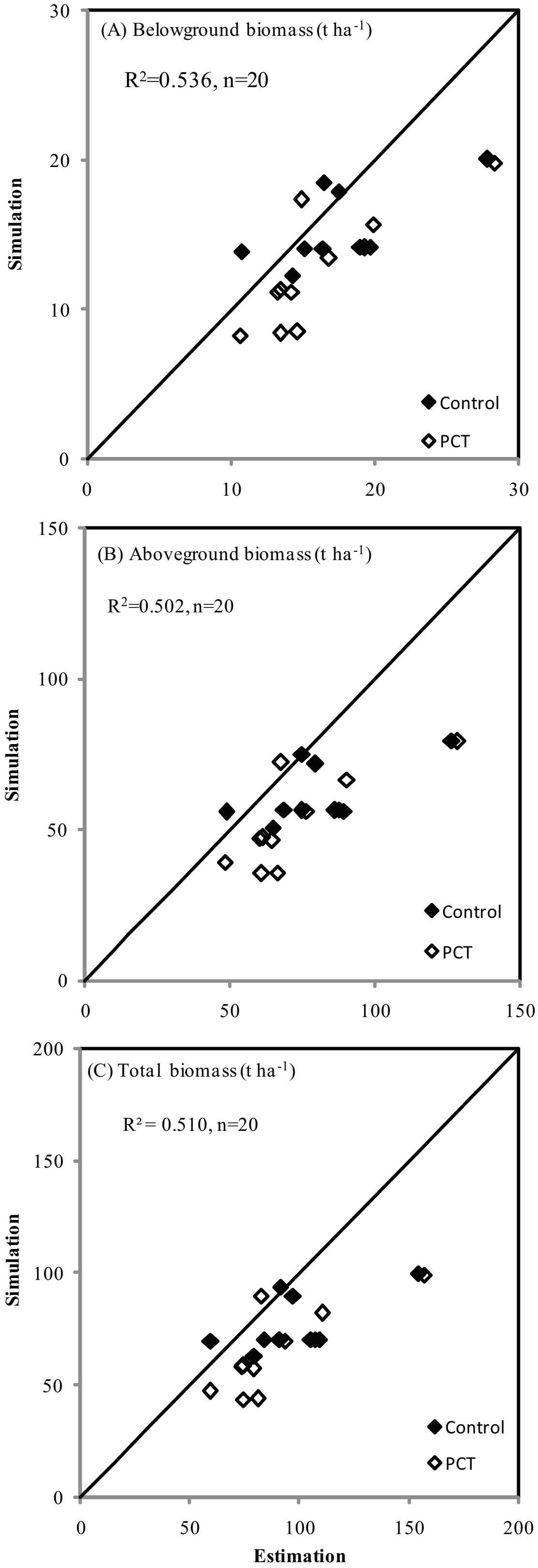

Fig. 4. Scatter plot comparisons between simulated and estimated (A) belowground biomass (t ha^{-1}), (B) aboveground biomass (t ha^{-1}), and (C) total biomass (t ha^{-1}) based on biomass equations for 20 Jack Pine stands located within 10 sites in Northwestern Ontario (Table 2). Solid diamonds represent control plots while hollow diamonds represent PCT plots. The solid diagonal representational line is the 1:1 line.

height, total stand volume, merchantable volume, biomass, and C pools. Management practices in terms of thinning in the 4C model is defined primarily by the intensity of thinning (e.g., basal area) and the size distribution of trees that were removed (Lasch et al., 2005). Thinning in the FinnFor model is first based on a reduction in basal area and then a conversion to stand density (Garcia-Gonzalo et al., 2007b). In addition, several adapted BGC versions (Tatarinov and Cienciala, 2006; Petritsch et al., 2007) rely on a reduction of biomass before converting stem C to volume growth per hectare using conversion factors. This study, however, simply tested the thinning intensity algorithm in relation to stand density and “thinning from below”. Other algorithms used to calculate thinning intensity (I_{Ba} and I_V) and “thinning from above” must therefore be further tested through a greater number of measurements in relation to both different species and different sites in the future.

4.2. Diameter distribution and PCT

The TRIPLEX-Management model is able to predict timber yield (DBH > 9 cm) and implement managerial practices through the incorporation of empirical Weibull diameter distributions. Moreover, results from this study suggest that Weibull distributions can fit well in relation to stand structure for both unthinned and thinned stands, even if stand diameter distribution is considerably altered by PCT.

Most process-based models such as TRIPLEX1.0 do not include stand structure components. Although the 4C model has been developed as a physiology-based gap model applying a cohort approach, empirical Weibull distributions are also used within the 4C model for pole-sized stands by means of a stochastic approach related to thinning (Lasch et al., 2005). Cohort approaches are also used within the FinnFor model (Kellomäki and Väisänen, 1997). The difference is the diameter distribution model is directly employed to quantify diameter distributions for thinned stands in the modified TRIPLEX-Management model. The model therefore does not predict diameter distributions in the five years after thinning occurs. The empirical Weibull diameter distribution model also underestimated the number of stems in the lower range of the diameter classes for certain PCT Jack Pine stands like site 1 (Fig. 3E). This was likely the result of the empirical diameter distribution model's inability to seize the benefit of more growth space that resulted from the thinning treatment.

4.3. Forest growth, yield, and PCT

TRIPLEX-Management captures mechanisms that accelerate tree growth, reduce mortality, and increase both productivity and timber production by way of adding litterfall pools and empirically decreasing residual stand mortality. Overall R^2 between the simulated and observed thinning effects were 0.69 ($n = 60$, $P < 0.001$) with a slope of 0.76 and an intercept of 0.07 (Fig. 5). Several studies pertaining to PCT in relation to Jack Pine stands have indicated that PCT has a considerable and positive effect on both DBH growth and individual stem volume growth (Morris et al., 1994; Tong and Zhang, 2005; Tong et al., 2005; Zhang et al., 2006). Similar results were found in most preceding experimental studies that investigated other tree species (Mäkinen and Isomaki, 2004b; Lei et al., 2007). A thinning simulation study conducted by Petritsch et al. (2007) also indicated that thinning enhances C allocation rates to stems and increases growth efficiency as a result of higher N use efficiency. This is according to the Monte-Carlo simulations used. Overall, the TRIPLEX-Management model is capable of simulating thinning management practices by incorporating a diameter distribution model.

Sensitivity analysis for thinning regimes (thinning time and thinning intensity) used in this study agrees with previous thinning experimental studies where trees generally grew larger in stands in which heavy intensity thinning treatments were applied (Mäkinen and Isomaki, 2004a; Simard et al., 2004; Lei et al., 2007). However, results from this study indicate that PCT may not necessarily lead to high stand level total yield, especially in relation to heavy thinning treatments. Results of this study are supported by Goble and Bowling (1993) and Tong et al. (2005).

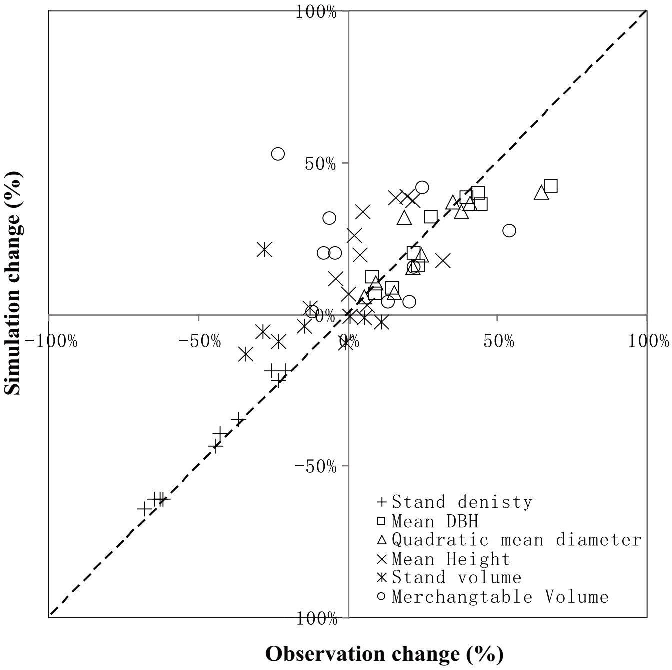

Fig. 5. Scatter plot comparisons between the effects of PCT (=[control – PCT]/control) on basic stand characteristics such as stand density (trees ha^{-1}), mean diameter at breast height (DBH) (cm), the quadratic mean diameter (cm), mean tree height (m), stand volume (m^3 ha^{-1}), and merchantable volume (DBH > 9 cm) (m^3 ha^{-1}) for 10 sites located within Northwestern Ontario in 2003. The dashed diagonal representational line is the 1:1 line.

4.4. Potential application and future work

The TRIPLEX-Management model developed for this study provides a realistic tool to predict forest growth, timber yield, biomass production, and C and N dynamics. Assuming that forest management can be accurately quantified by means of forest inventory data, wide application will require continued research on three fronts.

First, stand level forest simulation studies must include a broader range of forest types and thinning prescriptions, and must be carried out for longer timeframes. The data set used in this study was limited to a relatively small range in stand age (26–36 years). Moreover, it possessed a single PCT treatment and was comprised of a single stand type within the boundaries of a single region. One of the primary goals in developing the TRIPLEX1.0 model was to scale up from stand to regional scales (Peng et al., 2002). Regional application certainly depends on the composition of forest type, a broader age range, and diverse management strategies such as PCT, commercial thinning, harvesting, and N fertilization.

Second, it is critical to understand diameter distributions after forest management treatments take place for different tree species. Wood product value could be estimated based on size-dependent stem volume. For example, stand level product values were estimated using a combination of diameter distributions and individual tree product values (Newton and Amponsah, 2005). Forecasts for the stand level stem volume and merchantable volume or product value require a means to predict future diameter distributions

(Liu et al., 2009) and how diameter distribution is altered by forest management (e.g., thinning) decisions during forest development.

Third, forest thinning effects on soil C and N also require examination since soil C plays an important role in the global C cycle, especially in high latitude regions (Lal, 2005). Validation of the soil C pool was not possible in this study due to the lack of soil data available. Logistically speaking, PCT treatments may only result in a negligible disturbance on soil since heavy machinery is hardly used in this type of silvicultural treatment. Understanding changing processes in soil C and N dynamics under forest management practices, especially in relation to forest thinning, will prove important for model development and application.

5. Conclusions

TRIPLEX-Management, a new management submodel, was developed to simulate forest growth response to PCT treatments by way of incorporating diameter distribution into the TRIPLEX1.0 model. The implementation of forest thinning algorithms as reported by this study represents an important step towards improving the applicability of this process-based model for forest managers and industrial planning initiatives. Results demonstrate that the TRIPLEX-Management model is capable in capturing the growth response to PCT for Jack Pine stands in Northwestern Ontario, although the model has a systemic negative bias to stands that exhibit reasonably good site conditions. It still allows for the analysis of not only impacts of forest management strategies on forest growth, timber yield, biomass, and C sequestration but also how potential climate change can affect forest management for a given forest ecosystem. Overall, the TRIPLEX-Management model is a realistic and flexible tool in which to investigate the potential effects of management strategies on forest growth and yield, biomass production, and C dynamics.

Acknowledgements

This study was supported by the National Science and Engineering Research Council of Canada (NSERC) Strategic Project Grant, Strategic Network (ForValueNet) as well as by the company FPInnovations. The authors wish to thank the Canadian Centre for Climate Modelling and Analysis (CCCma) for supplying the data used in this analysis. They would also like to acknowledge Dr. Queju Tong for her published data set, Dr. Zhihai Ma for his help with statistics, Dr. Qiuan Zhu for his help with climate data processing, and Mr. Brian Doonan for his help on English editing.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2010.09.019.

References

Álvarez González, J.G., Schröder, J., Rodríguez Soalleiro, R., Ruíz González, A.D., 2002. Modelling the effect of thinnings on the diameter distribution of even-aged Maritime Pine stands. For. Ecol. Manage. 165, 57–65.

Battaglia, M., Sands, P., White, D., Mummery, D., 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. For. Ecol. Manage. 193, 251–282.

Bella, I.E., DeFranceschi, J., 1974. Commercial thinning improves growth of Jack Pine, Natural Resources Canada, Canadian Forestry Service – Northern Forestry Centre, Edmonton, AB. Information Report NOR-X-112, 23 pp.

Bossel, H., 1996. TREEDYN3 forest simulation model. Ecol. Model. 90, 187–227.

Brown, S., Sathaye, J., Cannell, M., Kauppi, P., Burschel, P., Grainger, A., Heuveldop, J., Leesman, R., Moura Costa, R., Pinard, M., 1996. Management of forests for mitigation of greenhouse gas emissions. In: Watson, R., Zinyowera, M., Moss, R. (Eds.), Climate Change 1995. Impacts, Adaptation and Mitigation of Climate Change: Scientific – Technical Analyses. Cambridge University Press, Cambridge, pp. 773–797.

Campbell, J., Alberti, G., Martin, J., Law, B.E., 2009. Carbon dynamics of a Ponderosa Pine plantation following a thinning treatment in the northern Sierra Nevada. For. Ecol. Manage. 257, 453–463.

Cao, Q.V., 2004. Predicting parameters of a weibull function for modeling diameter distribution. For. Sci. 50, 682–685.

Cienciala, E., Tatarinov, F.A., 2006. Application of BIOME-BGC model to managed forests: 2. Comparison with long-term observations of stand production for major tree species. For. Ecol. Manage. 237, 252–266.

Coops, N., Waring, R., Brown, S., Running, S., 2001. Comparisons of predictions of net primary production and seasonal patterns in water use derived with two forest growth models in Southwestern Oregon. Ecol. Model. 142, 61–81.

Garcia-Gonzalo, J., Peltola, H., Briceño-elizondo, E., Kellomäki, S., 2007a. Changed thinning regimes may increase carbon stock under climate change: a case study from a Finnish boreal forest. Clim. Change 81, 431–454.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., Kellomäki, S., 2007b. Effects of climate change and management on timber yield in boreal forests, with economic implications: a case study. Ecol. Model. 209, 220–234.

Goble, B.C., Bowling, C., 1993. Five-year Growth Response of Thinned Jack Pine Near Atikokan. Ontario Government, Ministry of Natural Resources, Ontario.

Groot, A., Brown, K., Morrison, I., Barker, J., 1984. A 10-year tree and stand response of Jack Pine to urea fertilization and low thinning. Can. J. For. Res. 14, 44–50.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268.

Johnsen, K., Samuelson, L., Teskey, R., McNulty, S., Fox, T., 2001. Process models as tools in forestry research and management. For. Sci. 47, 2–8.

Kellomäki, S., Väisänen, H., 1997. Modelling the dynamics of the forest ecosystem for climate change studies in the boreal conditions. Ecol. Model. 97, 121–140.

Kimball, J., Thornton, P., White, M., Running, S., 1997. Simulating forest productivity and surface-atmosphere carbon exchange in the BOREAS study region. Tree Physiol. 17, 589–600.

Komarov, A., Chertov, O., Zudin, S., Nadporozhskaya, M., Mikhailov, A., Bykhovets, S., Zudina, E., Zoubkova, E., 2003. EFIMOD 2 – a model of growth and cycling of elements in boreal forest ecosystems. Ecol. Model. 170, 373–392.

Korol, R.L., Milner, K.S., Running, S.W., 1996. Testing a mechanistic model for predicting stand and tree growth. For. Sci. 42, 139–153.

Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manage. 220, 242–258.

Lambert, M., Ung, C., Raulier, F., 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35, 1996–2018.

Landsberg, J., 2003. Modelling forest ecosystems: state of the art, challenges, and future directions. Can. J. For. Res. 33, 385–397.

Landsberg, J., Johnsen, K., Albaugh, T., Allen, H., McKeand, S., 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly Pine experiments. For. Sci. 47, 43–51.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manage. 95, 209–228.

Lasch, P., Badeck, F.-W., Suckow, F., Lindner, M., Mohr, P., 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). For. Ecol. Manage. 207, 59–74.

Lei, X., Lu, Y., Peng, C., Zhang, X., Chang, J., Hong, L., 2007. Growth and structure development of semi-natural larch-spruce-fir (Larix olgensis–Picea jezoensis–Abies nephrolepis) forests in northeast China: 12-year results after thinning. For. Ecol. Manage. 240, 165–177.

Li, Z., Kurz, W., Apps, M., Beukema, S., 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. 33, 126–136.

Liu, C., Beaulieu, J., Pregent, G., Zhang, S.Y., 2009. Applications and comparison of six methods for predicting parameters of the Weibull function in unthinned Picea glauca plantations. Scand. J. For. Res. 24, 67–75.

Liu, J., Peng, C., Dang, Q., Apps, M., Jiang, H., 2002. A component object model strategy for reusing ecosystem models. Comput. Electron. Agric. 35, 17–33.

Liu, L., Greaver, T., 2009. A review of nitrogen enrichment effects on three biogenic GHGs: the CO_2 sink may be largely offset by stimulated N_2O and CH_4 emission. Ecol. Lett. 12, 1103–1117.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20, 289–298.

Mäkinen, H., Isomaki, A., 2004a. Thinning intensity and growth of Scots Pine stands in Finland. For. Ecol. Manage. 201, 311–325.

Mäkinen, H., Isomaki, A., 2004b. Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. For. Ecol. Manage. 201, 295–309.

Matala, J., Hynynen, J., Miina, J., Ojansuu, R., Peltola, H., Sievänen, R., Väisänen, H., Kellomäki, S., 2003. Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. Ecol. Model. 161, 95–116.

Miehle, P., Battaglia, M., Sands, P.J., Forrester, D.I., Feikema, P.M., Livesley, S.J., Morris, J.D., Arndt, S.K., 2009. A comparison of four process-based models and a statistical regression model to predict growth of *Eucalyptus globulus* plantations. Ecol. Model. 220, 734–746.

Morris, D., Bowling, C., Hills, S., 1994. Growth and form responses to pre-commercial thinning regimes in aerially seeded Jack Pine stands: 5th year results. For. Chron. 70, 780–787.

Nabuurs, G.J., Thürig, E., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Mäkipää, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievanen, R., Somogyi, Z., Vallet, P., 2008. Hotspots of the European forests carbon cycle. For. Ecol. Manage. 256, 194–200.

Newcomer, J., Landis, D., Conrad, S., Curd, S., Huemmrich, K., Knapp, D., Morrell, A., Nickeson, J., Papagno, A., Rinker, D., 2000. Collected Data of the Boreal Ecosystem-Atmosphere Study. CD-ROM, NASA, Goddard Space Flight Center, Greenbelt, MD.

Newton, P., Amponsah, I., 2005. Evaluation of Weibull-based parameter prediction equation systems for black spruce and Jack Pine stand types within the context of developing structural stand density management diagrams. Can. J. For. Res. 35, 2996–3010.

Nord-Larsen, T., Cao, Q.V., 2006. A diameter distribution model for even-aged beech in Denmark. For. Ecol. Manage. 231, 218–225.

Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H., Kellomäki, S., 2006. Regionally optimized forest management under changing climate. Clim. Change 79, 315–333.

Parton, W., Scurlock, J., Ojima, D., Gilmanov, T., Scholes, R., Schimel, D., Kirchner, T., Menaut, J., Seastedt, T., Moya, E., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7, 785–809.

Peng, C., 2000. Understanding the role of forest simulation models in sustainable forest management. Environ. Impact Assess. Rev. 20, 481–501.

Peng, C., Apps, M., Price, D.T., 1998. Simulation carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in central Canada. Glob. Biogeochem. Cycle 12, 381–402.

Peng, C., Liu, J., Dang, Q., Apps, M.J., Jiang, H., 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. Ecol. Model. 153, 109–130.

Peng, C., Zhou, X., Zhao, S., Wang, X., Zhu, B., Piao, S., Fang, J., 2009. Quantifying the response of forest carbon balance to future climate change in Northeastern China: model validation and prediction. Glob. Planet. Change 66, 179–194.

Petritsch, R., Hasenauer, H., Pietsch, S.A., 2007. Incorporating forest growth response to thinning within biome-BGC. For. Ecol. Manage. 242, 324–336.

Plonski, W.L., 1974. Normal yield tables (metric) for major forest species of Ontario. Ontario Ministry of Natural Resources, Toronto.

R Development Core Team, 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0, URL http://www.R-project.org.

Running, S., Gower, S., 1991. FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree Physiol. 9, 147–160.

Running, S., Hunt, E., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: Ehleringer, J., Field, C. (Eds.), Scaling Physiological Processes: Leaf to Globe. Academic Press, San Diego, CA, pp. 141–158.

Ryan, M., Lavigne, M., Gower, S., 1997. Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate. J. Geophys. Res. 102, 28871–28884.

Sands, P.J., Battaglia, M., Mummery, D., 2000. Application of processbased models to forest management: experience with PROMOD, a simple plantation productivity model. Tree Physiol. 20, 383–392.

Simard, S.W., Blenner-Hassett, T., Cameron, I.R., 2004. Pre-commercial thinning effects on growth, yield and mortality in even-aged paper birch stands in British Columbia. For. Ecol. Manage. 190, 163–178.

Smith, D.M., Larson, B.C., Kelty, M.J., Ashton, P.M.S., 1997. The Practice of Silviculture: Applied Forest Ecology. Wiley, New York.

Steele, S., Gower, S., Vogel, J., Norman, J., 1997. Root mass, net primary production and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitoba, Canada. Tree Physiol. 17, 577–588.

Tatarinov, F.A., Cienciala, E., 2006. Application of BIOME-BGC model to managed forests: 1. Sensitivity analysis. For. Ecol. Manage. 237, 267–279.

Thornley, J.H., Cannell, M.G., 2000. Managing forests for wood yield and carbon storage: a theoretical study. Tree Physiol. 20, 477–484.

Tong, Q.J., Zhang, S.Y., 2005. Impact of initial spacing and precommercial thinning on tree growth and stem quality in Jack Pine. For. Chron. 81, 418–428.

Tong, Q.J., Zhang, S.Y., Thompson, M., 2005. Evaluation of growth response, stand value and financial return for pre-commercially thinned Jack Pine stands in Northwestern Ontario. For. Ecol. Manage. 209, 225–235.

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change, Bonn, Germany. Document FCCC/CP/1997/7/Add.1. http://www.unfccc.int.

Vesala, T., Suni, T., Rannik, Ü., Keronen, P., Markkanen, T., Sevanto, S., Grönholm, T., Smolander, S., Kulmala, M., Ilvesniemi, H., Ojansuu, R., Uotila, A., Levula, J., Mäkelä, A., Pumpanen, J., Kolari, P., Kulmala, L., Altimir, N., Berninger, F., Nikinmaa, E., Hari, P., 2005. Effect of thinning on surface fluxes in a boreal forest. Global Biogeochem. Cycles 19, doi:10.1029/2004GB002316.

Wallman, P., Svensson, M.G.E., Sverdrup, H., Belyazid, S., 2005. ForSAFE – an integrated process-oriented forest model for long-term sustainability assessments. For. Ecol. Manage. 207, 19–36.

Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteor. Soc. 63, 1309–1313.

Zarnoch, S.J., Roamm, C.W., Rudolph, V.J., Day, M.W., 1982. The Effects of Red Pine Thinning Regimes on Diameter Distribution Fitted to the Weibull Function. Michigan State University, Agricultural Experiment Station, East Lansing.

Zhang, J., Chu, Z., Ge, Y., Zhou, X., Jiang, H., Chang, J., Peng, C., Zheng, J., Jiang, B., Zhu, J., Yu, S., 2008. TRIPLEX model testing and application for predicting forest growth and biomass production in the subtropical forest zone of China's Zhejiang Province. Ecol. Model. 219, 264–275.

Zhang, L., Peng, C., Huang, S., Zhou, X., 2002. Development and evaluation of ecoregion-based Jack Pine height-diameter models for Ontario. For. Chron. 78, 530–538.

Zhang, S.Y., Chauret, G., Swift, D.E., Duchesne, I., 2006. Effects of precommercial thinning on tree growth and lumber quality in a Jack Pine stand in New Brunswick, Canada. Can. J. For. Res. 36, 945–953.

Zhou, X., Peng, C., Dang, Q.-L., Chen, J., Parton, S., 2005. Predicting forest growth and yield in northeastern Ontario using the process-based model of TRIPLEX1.0. Can. J. For. Res. 35, 2268–2280.

Zhou, X., Peng, C., Dang, Q.-L., Sun, J., Wu, H., Hua, D., 2008. Simulating carbon exchange in Canadian Boreal forests: I. Model structure, validation, and sensitivity analysis. Ecol. Model. 219, 287–299.

Zhou, X., Peng, C., Dang, Q., 2004. Assessing the generality and accuracy of the TRIPLEX model using in situ data of boreal forests in central Canada. Environ. Model. Softw. 19, 35–46.