Predicting forest growth and yield in northeastern Ontario using the process-based model of TRIPLEX1.0[1]

Xiaolu Zhou, Changhui Peng, Qing-Lai Dang, Jiaxin Chen, and Sue Parton

Abstract: Process-based carbon dynamic models are rarely validated against traditional forest growth and yield data and are difficult to use as a practical tool for forest management. To bridge the gap between empirical and process-based models, a simulation using a hybrid model of TRIPLEX1.0 was performed for the forest growth and yield of the boreal forest ecosystem in the Lake Abitibi Model Forest in northeastern Ontario. The model was tested using field measurements, forest inventory data, and the normal yield table. The model simulations of tree height and diameter at breast height (DBH) showed a good agreement with measurements for black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), and trembling aspen (*Populus tremuloides* Michx.). The coefficients of determination (R^2) between simulated values and permanent sample plot measurements were 0.92 for height and 0.95 for DBH. At the landscape scale, model predictions were compared with forest inventory data and the normal yield table. The R^2 ranged from 0.73 to 0.89 for tree height and from 0.72 to 0.85 for DBH. The simulated basal area is consistent with the normal yield table. The R^2 for basal area ranged from 0.82 to 0.96 for black spruce, jack pine, and trembling aspen for each site class. This study demonstrated the feasibility of testing the performance of the process-based carbon dynamic model using traditional forest growth and yield data and the ability of the TRIPLEX1.0 model for predicting growth and yield variables. The current work also introduces a means to test model accuracy and its prediction of forest stand variables to provide a complement to empirical growth and yield models for forest management practices, as well as for investigating climate change impacts on forest growth and yield in regions without sufficient established permanent sample plots and remote areas without suitable field measurements.

Résumé : Les modèles basés sur les processus de la dynamique du carbone sont rarement validés avec des données traditionnelles de croissance et rendement des forêts et sont difficiles à utiliser comme outil pratique en aménagement forestier. Afin de créer des liens entre les modèles empiriques et les modèles basés sur les processus, une simulation utilisant le modèle hybride TRIPLEX1,0 a été réalisée pour la croissance et le rendement des forêts dans l'écosystème forestier boréal de la forêt modèle du Lac Abitibi dans le nord-est de l'Ontario. Le modèle a été testé en utilisant des données de terrain, des données d'inventaire et la table de rendement normal. Les simulations du modèle de la hauteur et du diamètre à hauteur de poitrine (DHP) ont montré une bonne correspondance avec les mesures pour l'épinette noire (*Picea mariana* (Mill.) BSP), le pin gris (*Pinus banksiana* Lamb.) et le peuplier faux-tremble (*Populus tremuloides* Michx.). Les coefficients de détermination (R^2) entre les valeurs simulées et les mesures des parcelles échantillons permanentes étaient de 0,92 pour la hauteur et de 0,95 pour le DHP. À l'échelle du paysage, les prédictions du modèle ont été comparées aux données d'inventaire forestier et aux tables de rendement. Le R^2 variait de 0,73 à 0,89 pour la hauteur de l'arbre et de 0,72 à 0,85 pour le DHP. La surface terrière simulée est consistante avec la table de rendement normal. Le R^2 pour la surface terrière variait de 0,82 à 0,96 pour chaque classe de station des trois espèces mentionnées plus haut. Cette étude a démontré qu'il était possible de tester la performance des modèles basés sur les processus de la dynamique du carbone avec des données traditionnelles de croissance et rendement des forêts et que le modèle TRIPLEX1,0 était capable de prédire les variables de croissance et rendement. L'article a aussi introduit un moyen de tester l'exactitude du modèle et sa prédiction des variables d'un peuplement forestier pour fournir un complément aux modèles empiriques de croissance et rendement pour les pratiques d'aménagement forestier, ainsi que pour examiner

X. Zhou,[2] Q.-L. Dang, and J. Chen. Faculty of Forestry and the Forest Environment, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1, Canada

C. Peng.[3] Institut des sciences de l'environnement, Département des sciences biologiques, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, QC H3C 3P8, Canada.

S. Parton. Lake Abitibi Model Forest, Box 129, 143 Third Street, Cochrane, ON P0L 1C0, Canada.

[1]This article is one of a selection of papers published in the Special Issue on Climate–Disturbance Interactions in Boreal Forest Ecosystems.

[2]Present address: Environmental Monitoring Section, Applications Division, Canada Centre for Remote Sensing, Natural Resources Canada, 588 Booth Street, Ottawa, ON K1A 0Y7, Canada.

[3]Corresponding author (e-mail: peng.changhui@uqam.ca).

doi: 10.1139/X05-149

l'impact des changements climatiques sur la croissance et le rendement des forêts dans des régions où il n'y a pas suffisamment de parcelles échantillons permanentes et des régions éloignées où il n'y a pas de mesures de terrain appropriées.

[Traduit par la Rédaction]

Introduction

Global warming is an issue of concern for sustainable forest management. Warming in the boreal region may result in large-scale displacement and redistribution of boreal forests (Emanuel et al. 1985; Pastor and Post 1988; Neilson and Marks 1994). This climate change affects both total carbon budget and total amount of biomass, and the dynamics of forest ecosystems can also feedback to the climate system. To implement sustainable forest management, forest managers are currently facing an important challenge: understanding and predicting the potential impacts of increasing atmospheric temperature and CO_2 concentrations on the dynamics of forest growth and productivity. Traditionally, empirical statistical models (growth and yield models) have been used to estimate tree height, diameter at breast height (DBH), and total volume. Unfortunately, these statistical models are unable to simulate either the impacts of future climate change on forest stands or the forest growth dynamics of some regions as a result of the lack of historical data, because they predict growth and yield completely based on past measurement and simulate forests without considering climate variables such as temperature, precipitation, and the change in CO_2 concentration (Kimmins 1993; Bossel 1996; Peng 2000).

To improve these shortcomings of empirical statistical models, a number of process-based models have been developed (Running and Coughlan 1988; Parton et al. 1993; Kimmins 1993; Korol et al. 1994; Kimmins and Scoullar 1995; Bossel 1996; Landsberg and Waring 1997) for describing complex interacting processes in forest ecosystems. Bossel (1991) and Kimmins (1993) have reviewed the historical developments of the process-based models; Battaglia and Sands (1998), Landsberg and Coops (1999), Mäkelä et al. (2000), and Peng (2000) have recently discussed the features and specifications of process-based models for applications in sustainable forest management. As these researchers suggested, process-based models have obvious advantages for predicting future ecosystem structure and functions under different scenarios of climate change, silviculture practices, and land use. However, most process-based models are not able to simulate the forest stand variables (e.g., tree height, DBH, volume) because they are not designed for forest management and do not predict forest stand attributes. Although a few models (3-PG, Landsberg and Waring 1997; TREEDYN3, Bossel 1996; PROMOD, Sands et al. 2000; FVSBGC, Milner et al. 2003) have functions to simulate the forest growth and yield variables, there has been no independent evaluation of these models using large growth and yield data sets from Canadian boreal forest ecosystems.

In this paper, we present the results of a model simulation for the Lake Abitibi Model Forest (LAMF) using TRIPLEX1.0 (Peng et al. 2002), which has empirical and mechanistic components. This model calculates tree height and diameter increments from stem biomass, and then derives basal area and volume based on tree density (stems per hectare). The objectives of this study were (1) to validate the hybrid model of TRIPLEX1.0 for simulating tree height, diameter, and basal area using the forest growth and yield data collected in the LAMF and (2) to simulate forest stand volume and its spatial distribution in the LAMF for the 1990s.

Materials and methods

Site information

The LAMF is one of 11 model forests that have been supported by Canadian Model Forest Program. It has a total area of 1.2×10^6 ha in the boreal forest of northeastern Ontario, approximately 0.9×10^6 ha of which is forest (Fig. 1). The LAMF is divided by Iroquois Falls into two parts: Iroquois Falls North has a forest land area of 0.77×10^6 ha, and Iroquois Falls South has approximately 0.13×10^6 ha. Both areas are located at the central part of the Clay Belt region in northern Ontario. The soils in the LAMF are primarily fine-textured clays, covered by organic deposits in poorly drained areas (Griffin 2001). The area proportions of soil composition in the LAMF are 65% clay, 2% clay and medium sand, 16% fine sand, 2% medium sand, and 15% unclassified (Fig. 1). Three primary species, black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banskiana* Lamb.), and trembling aspen (*Populus tremuloides* Michx.), cover more than 80% of the area. The average stand age of the forest in the LAMF was over 170 years in 2000 (Bergeron et al. 2001). The climate of LAMF and its associated weather conditions are influence by James Bay to the north (Environment Canada 2000). It is characterized as a humid continental climate with short, cool to moderately warm summers and long, cold to severe winters. In 1990 the annual average temperature was 1.6 °C and annual precipitation was 976 mm (48.8°N lat., 80.7°W long.; Environment Canada 1994).

Data sources

To simulate forest growth and yield dynamics in an ecosystem, we used data compiled from five different sources.

Forest stands

The model simulation required stand data on stand type, forest type, tree age, stocking, site class, and tree species for simulating each different stand. These stand data were derived from the 1993 Iroquois Falls Forest Inventory, which provides information for a total of 44 343 forest stands in the LAMF. More than 92% of the dominant species are black spruce, jack pine, and trembling aspen. The tree height data in the inventory were photointerpreted by forest professionals using ground sample plot data for calibration, and averaged DBH was derived using Plonski yield tables. Vegetation data in ArcView GIS format for each stand were obtained from the LAMF.

Fig. 1. The location, road network, permanent sample plot distribution, and soil texture of the Lake Abitibi Model Forest.
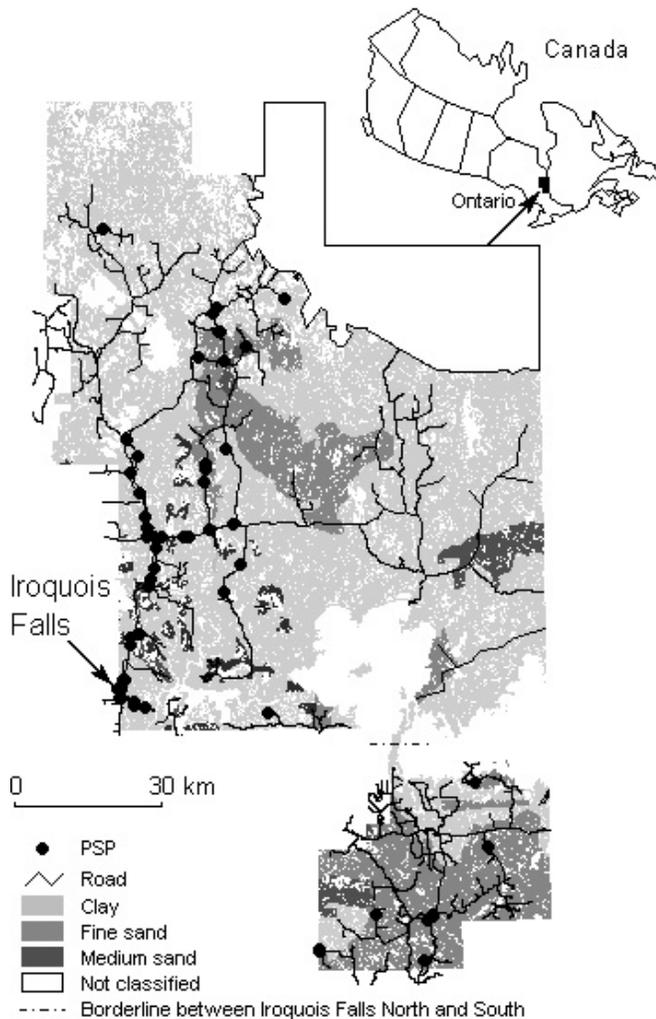
Permanent sample plots (PSP)

The distribution and locations of 49 PSPs in the LAMF are presented in Fig. 1. These PSPs contain three major boreal tree species: black spruce, jack pine, and trembling aspen. Their stand ages ranged from 11 to 193 years (Ontario Ministry of Natural Resources 1996).

Soil texture

We used the Ontario Land Inventory and Primeland/Site Information System (OLIPSIS; Elkie et al. 2000), which presented the details of soil texture in Ontario forest ecoregions. Additional soil databases (Siltanen et al. 1997; Centre for Land and Biological Resources Research 1993; Oak Ridge National Laboratory 2002) were referenced as well.

Climate conditions

Monthly climate variables were used in the simulations of forest growth, productivity, biomass, and soil carbon. Average temperature and precipitation were obtained from the climate database developed by Canadian Centre for Climate Modelling and Analysis (CCCma 2003). The climate data for monthly temperature and precipitation with the grid format were interpolated using the downscaling technique

(Oelschlagel 1995) for obtaining representative values for each stand. The detailed interpolation of climate variables was reported in Zhou et al. (2004a).

Spatial net primary productivity (NPP) data

TRIPLEX1.0 provides simulated NPP, which is one of key output variables for quantifying ecosystem productivity. Because of the lack of field measurements, we compared modeled NPP with the NPP distribution estimated from remote sensing at the landscape level. The NPP distribution (1 km × 1 km grid resolution) reported by Liu et al. (2002) for 1994 was derived from remote sensing and upscaled (3 km × 3 km resolution) for comparison with modeled NPP at landscape levels in this study.

The TRIPLEX model

Model structure

TRIPLEX1.0 is a generic hybrid model that simulates the key processes of the carbon cycle in an ecosystem. One of its special features is the ability to simulate growth and yield for a stand based on ecological mechanisms and provide growth and yield information derived from simulated stand biomass allocations. As TRIPLEX1.0 combines the advantages of both empirical and process-based models, it bridges the gap between empirical forest growth and yield and process-based carbon balance models (Peng et al. 2002). The key variables of carbon dynamics of the forest ecosystem are included in the simulation, such as photosynthetically active radiation (PAR), gross primary productivity (GPP), NPP allocation, forest growth and yield, soil carbon, soil nitrogen, and soil water. The model structure is shown in Fig. 2 and its four parts are summarized as follows:

(1) Forest production. It estimates PAR and GPP including above- and below-ground biomass. The PAR was calculated as a function of the solar constant, radiation fraction, solar height, and atmospheric absorption. The initial PAR and solar radiation fraction were estimated as constants (1360 W·m^{-2} and 0.47, respectively) (Bossel 1996). The solar height is calculated depending on the latitude of the site and the time of day. Monthly PAR received by the forest canopy is estimated using cloud ratios. The model calculates monthly GPP from received PAR, mean air temperature, vapour pressure deficit, soil water, percentage of frost days, and leaf area index. The NPP/GPP ratio of 0.39 was chosen for the boreal forest ecosystem (Ryan et al. 1997). The NPP is then partitioned into parts of the tree using a set of functions that depend on tree age. Total biomass growth is simulated by accumulating monthly increment.

(2) Soil carbon and nitrogen. The dynamics of soil carbon and nitrogen were simulated for the litter and soil pools. This submodel was based on CENTURY soil decomposition modules (Parton et al. 1987, 1993), because it provides realistic estimates of both carbon and nitrogen mineralization rates for Canadian boreal forest ecosystems (Peng et al. 1998). Decomposition rates of soil carbon for each carbon pool were calculated as functions of maximum decomposition rates, effects of soil moisture, and soil temperature.

There were two separate feedbacks from "decomposition" to nitrogen pools and atmospheric CO$_2$ (see Fig. 2). The ni-

Fig. 2. The structure of forest growth and carbon simulation model TRIPLEX1.0 (modified from Peng et al. 2002). Rectangles represent key pools or state variables, ovals represent core simulation processes, dotted lines represent controls, and solid lines represent flows of carbon (C), nitrogen (N), water, and the fluxes between the forest ecosystem and external environment. Two arrow cycles refer to two feedbacks.
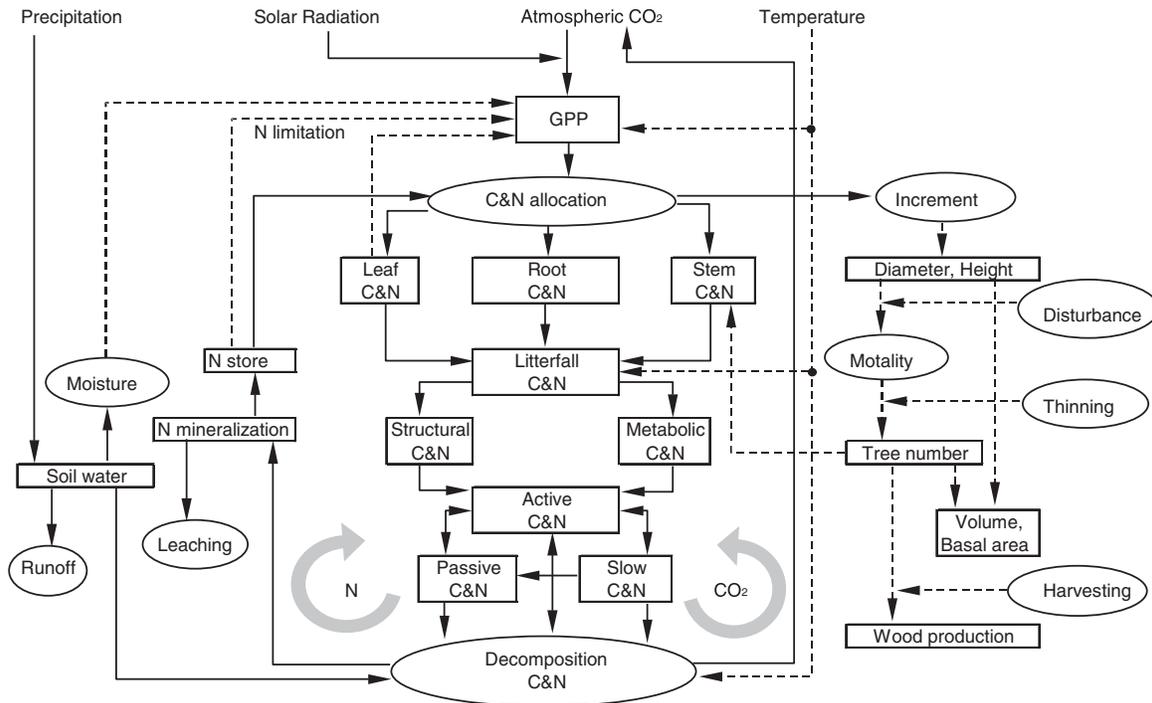
trogen pool (nitrogen store) plays a role as an output of the soil submodel (CENTURY soil model) and input for the forest production submodel. The nitrogen level in this pool affects NPP and tree growth in each simulation step. Assuming that actual NPP is usually lower than potential NPP if taking nitrogen limitation into account, available NPP was calculated using a nitrogen-limited equation:

[1]   Available NPP = Ccpp f_r GPP

[2] $f_r = \dfrac{NR_{cn}}{\text{Potential NPP}}$ $(0 \leq f_r \leq 1)$

where Ccpp is a ratio of potential NPP to GPP, f_r represents the nitrogen limitation function, N is available nitrogen, and R_{cn} is maximum C:N.

(3) Forest growth and yield. The major variables of tree growth and yield were derived from biomass increment. The key variable is the increment of tree diameter, which was calculated using a function of stem wood biomass increment (Bossel 1996):

[3] $R_d = \dfrac{4G}{\pi c f D^2 (2H/D + F_{hd})}$

[4] $f_{hd} = \begin{cases} F_{hdmin} & (C_r < H/D \geq F_{hdmin}) \\ F_{hdmin} & (C_r \geq H/D \leq F_{hdmmax}, A < 05A_{max}) \\ 0.5F_{hdmin} & (H/D > F_{hdmax}) \\ F_{hdmax} & (Cr \geq 1, H/D \leq F_{hdmax}) \\ F_{hdmax} & (H/D < F_{hdmin}) \\ 0 & (A > 0.7A_{max}) \end{cases}$

[5] C_r = crown area × tree density

where R_d is individual DBH increment (cm), G is stem wood biomass increment (tC·tree^{-1}), c is wood carbon density (tC·m^{-3}), f is tree form factor, D is DBH (cm), H is height (m); F_{hd} is the tree growth factor related to crown competition coefficient (C_r), tree age (A), maximum tree age (A_{max}), and minimum (F_{hdmin}) and maximum (F_{hdmax}) tree growth factors.

Because height and diameter growth are influenced by a combination of physiological and morphological responses to environmental factors, height/diameter ratio is used as an alternative competition index to determine the free growth status. We used the assumptions of Bossel (1996) for processing crown competition (i.e., $C_r \geq 1$), which supposed that trees grow more in height with, and more in diameter without, the competition. Once crown competition occurs, the total mortality contains both normal and crowding mortality. If thinning occurs, living biomass can be calculated using remaining tree number, which reflects both thinning and tree mortality. After thinning, C_r will be recalculated for simulating in the next time step.

(4) Soil water balance. This component is a simplified water budget module that calculates monthly water loss through transpiration, evaporation, soil water contentl, and snow water content. It is a part of soil water submodel of the CENTURY model for simulating water balance and dynamics. This submodel requires precipitation as an input, then converts it to snow depending on air temperature, and outputs transpiration, evaporation, and leached water to other submodels.

Recently, TRIPLEX1.0 has been parameterized (see Appendix A) and successfully calibrated for pure jack pine stands

Fig. 3. The comparisons of tree height and DBH between simulations and observations from permanent sample plots in the Lake Abitibi Model Forest (height: $\bar{e}$ = 0.51, S_e = 1.80, bias = 3.9%, p < 0.003; DBH: $\bar{e}$ = 0.32, S_e = 1.68, bias = 2.1%, p < 0.031). Field data were measured and updated in 1995 (Ontario Ministry of Natural Resources, 1996) for 32 black spruce, 9 jack pine, and 8 trembling aspen plots, respectively.

height, tree density, basal area, and volume), which were summed up yearly for the final outputs of the model.

This study performed regional runs that required initialization in a spatial dimension. The OLIPIS soil data sets (Elkie et al. 2000) provide a provincial soil carbon distribution classified as high, moderate, and low levels. We adopted the average value of 118 tC·ha⁻¹ estimated by Kurz et al. (1992) as the initial soil carbon level corresponding to a "moderate" level for the Boreal West area and assumed 118 ± 15 tC·ha⁻¹ (mean ± standard error) corresponding to "high" and "low" levels, respectively. A lower level (0.02 t·ha⁻¹) was assumed for the initial nitrogen level for all the stands. All initial stand biomass started at zero from May of the regeneration year. The spatial pattern of tree density was initialized depending on the species and its distribution. We assumed initial tree density to be 20 000, 20 000, and 5000 stems·ha⁻¹ for black spruce, jack pine, and trembling aspen stands in the regeneration year. Subsequent stand density is simulated from the initial density and crowding mortality once competition starts.

Results

Model validation

As shown in Fig. 2, TRPLEX1.0 calculated average tree height and diameter increments from stem wood mass increment. The model with such a structure produced reasonable outputs for growth and yield, which reflect the impact of climate variability over time. To test the model's accuracy, we compared the simulated height and DBH with average PSP measurements in the LAMF. The comparison shows high coefficients of determination (R^2) (0.92 for height and 0.95 for DBH), small errors (0.51 for height and 0.32 for DBH), and low biases (3.9% for height and 2.1% for DBH) (Fig. 3) for the three main boreal species: black spruce, jack pine, and trembling aspen. To conduct a model validation using large samples of growth and yield data in boreal forest ecosystems at the regional scale, we also compared simulations with observations (derived from 1993 Iroquois Falls Forest Inventory) for average tree height and DBH in stands of black spruce, jack pine, and trembling aspen in the LAMF, but juvenile stands (total height < breast height) were excluded for the model testing. The R^2 were greater than 0.72 for all three primary tree species (see Table 2, Fig. 4). Black spruce had a higher R^2 ($\geq$ 0.85) for both tree height and DBH than jack pine and trembling aspen.

Because field data on tree density were lacking, we used basal area curves from normal yield tables to compare model prediction. Table 1 presents the results of comparison and statistical analysis, and Fig. 5 shows an example of the comparison for basal area for black spruce site class 1. The R^2 between simulated basal area (m²·ha⁻¹) and that from the normal yield table ranged from 0.82 to 0.96 (Table 1) for the three tree species and all site classes. The mean prediction errors and biases were calculated for tree height, DBH, and basal area by tree species (black spruce, jack pine, and trembling aspen) and site class (Tables 1 and 2). The biases (average prediction error divided by average observation) were within ±20% for tree height, DBH, and basal area. All p values were less than the critical value at α = 0.05. Overall,

in Ontario (Peng et al. 2002; Liu et al. 2002), using 12 permanent sample plots measured by Kimberly-Clark Limited between 1950 and 1980, and for major boreal tree species in central Canada (Zhou et al. 2004b) using field data from the Boreal Ecosystem–Atmosphere Study (BOREAS) (Newcomer et al. 2000), before being applied to the LAMF in this study.

Simulation runs

As TRIPLEX1.0 simulates the whole growth period of trees, each stand was simulated from the regeneration year to the year specified for forest estimation. All simulations were conducted with a monthly time step under different climate conditions. The model calculated monthly increments of each component of tree biomass (including leaves, stems, and roots), and derived stand yield variables (i.e., DBH,

Fig. 4. The comparisons of tree height and DBH between simulations and estimations for the Lake Abitibi Model Forest. Estimated values were based on the 1993 Iroquois Falls Forest Inventory. *n*, number of stands.
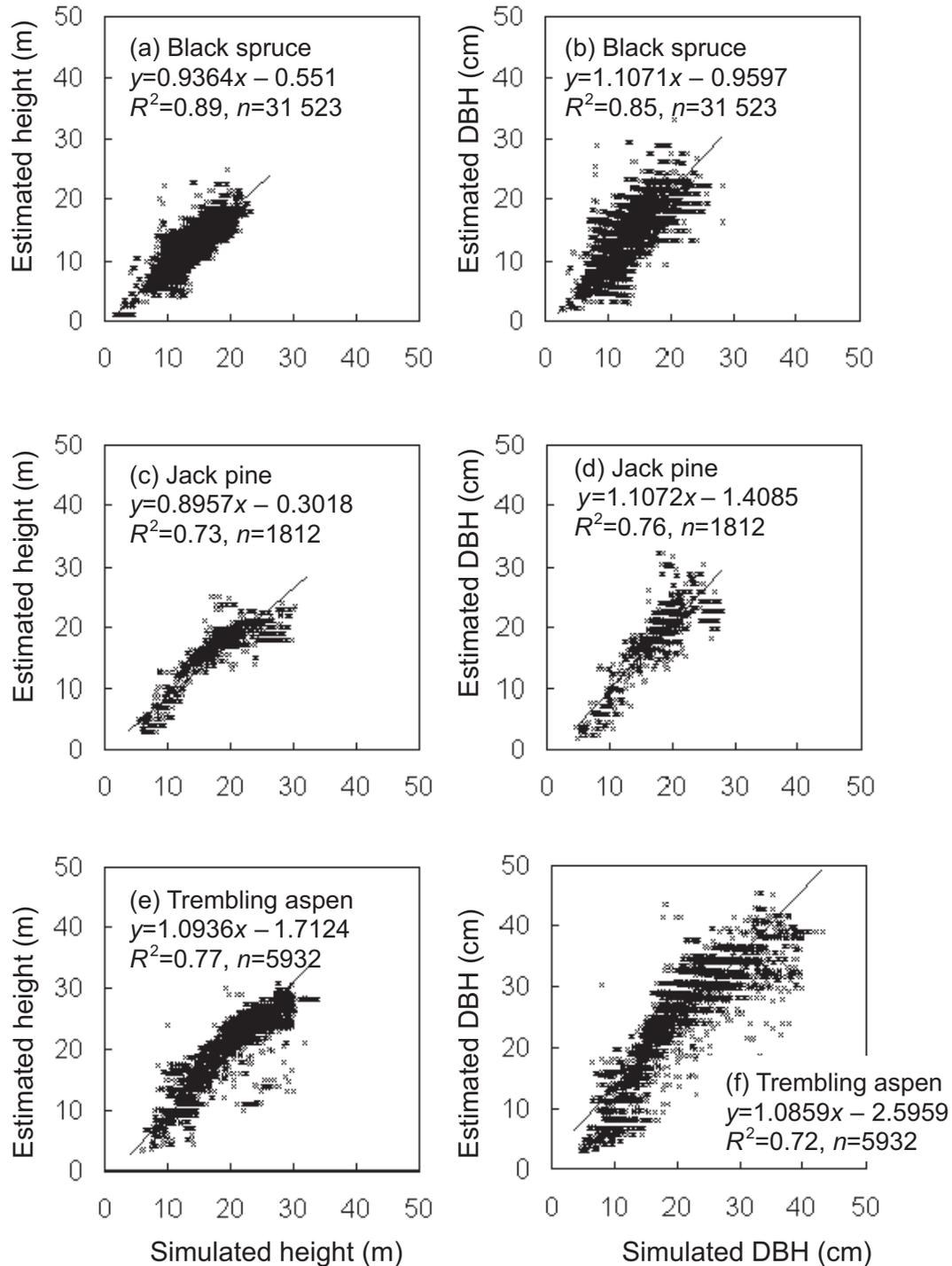
simulated values for black spruce showed higher R^2 and lower bias than those for jack pine and trembling aspen.

The simulated NPP distribution was also compared with the NPP estimated from remote sensing data at the landscape level (Fig. 6). The agreement of NPP spatial distribution between Fig. 6a (TRIPLEX1.0 simulations) and Fig. 6b (estimations from remote sensing approach of Liu et al. 2002) was measured using the kappa statistic (*K*), which measures the grid cell by grid cell agreement between the two maps

(Cohen 1960; Monserud 1990). Monserud (1990) and Prentice et al. (1992) uses the following qualitative descriptors to characterize the degree of agreement based on *K*: very poor to poor agreement if *K* < 0.4, fair agreement if 0.4 < *K* < 0.55, good agreement if 0.55 < *K* < 0.7, very good agreement if 0.7 < *K* < 0.85, and excellent agreement if *K* > 0.85. The overall *K* value was about 0.51, suggesting a fair agreement between Figs. 6a and 6b. In addition, the simulated distribution of NPP for LAMF was within the range of 2.2–

Fig. 5. The comparisons of basal area between simulations and the normal yield table for the Lake Abitibi Model Forest (black spruce, site class 1). The solid line denotes the basal area curve from the normal yield table (Plonski 1974). Error bars represent standard errors (black bars) and distribution ranges (gray bars, $n = 11\ 425$).
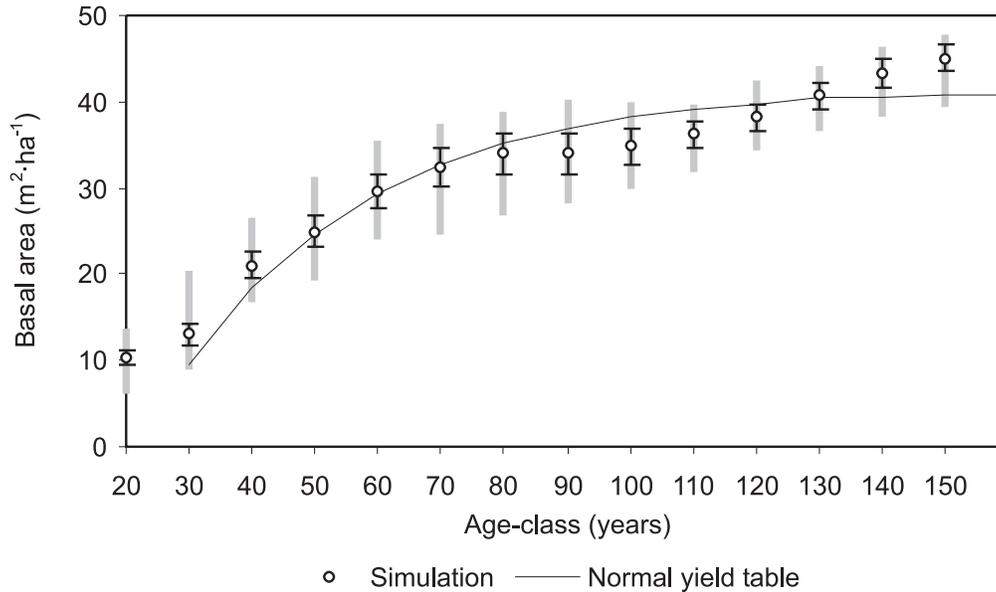
Table 1. The comparisons of basal area between simulations and the normal yield table (Plonski 1974) at the Lake Abitibi Model Forest for site classes 1, 2, and 3.

	Black spruce			Jack pine			Trembling aspen			Range	
	1	2	3	1	2	3	1	2	3	Min.	Max.
n	1425	14 540	5558	343	1200	269	905	4593	343	343	14 540
R^2	0.93	0.96	0.88	0.82	0.93	0.88	0.95	0.95	0.93	0.82	0.96
$\bar{e}$	2.09	1.94	3.13	−1.71	−3.12	−0.54	1.88	4.51	4.40	−3.12	4.51
S_e	1.67	2.61	5.44	6.36	4.00	1.67	2.16	1.46	2.13	1.46	6.36
Bias (%)	6.27	6.65	12.32	−6.50	−12.99	−2.63	6.19	15.93	18.20	−12.99	18.20
p value	<0.017	<0.001	<0.001	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.001	<0.017

Note: n, sample size (number of stands); R^2, coefficient of determination; $\bar{e}$, average of prediction error; S_e, standard deviation of prediction error.

Table 2. Prediction errors of the TRIPLEX1.0 model applied to each stand for three dominant species in the Lake Abitibi Model Forest, comparing height and DBH between simulations and field data observed in 1993.

	Black spruce				Jack pine				Trembling aspen			
	1	2	3	Total	1	2	3	Total	1	2	3	Total
Tree height (m)												
R^2	0.80	0.89	0.93	0.89	0.89	0.72	0.90	0.73	0.69	0.78	0.82	0.77
$\bar{e}$	0.87	−0.80	−2.00	−0.59	−1.91	−2.13	−0.88	−1.89	−1.26	0.58	1.17	0.33
S_e	1.79	2.10	1.56	2.20	2.22	3.46	1.69	2.81	3.75	2.41	2.28	2.62
Bias (%)	6.42	−6.28	−18.35	−4.75	−12.2	−12.01	−6.08	−11.99	−10.30	2.73	6.79	1.55
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
DBH (cm)												
R^2	0.76	0.86	0.90	0.85	0.93	0.74	0.87	0.76	0.75	0.68	0.87	0.72
$\bar{e}$	0.7	1.57	−0.87	0.62	1.95	1.12	−0.78	0.49	2.87	4.49	2.97	4.11
S_e	3.17	2.73	2.02	3.01	3.43	3.03	2.43	3.43	7.45	5.05	4.16	5.07
Bias (%)	4.43	10.79	−7.27	4.42	10.84	5.36	−4.86	2.72	10.57	17.88	16.2	16.47
p value	< 0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
n	11 425	14 540	5558	31 523	343	1200	269	1812	905	4593	434	5932

Note: n, sample size (number of stands); $\bar{e}$, average of prediction error; S_e, standard deviation of prediction error.

Fig. 6. The comparison at landscape levels between (*a*) net primary productivity (NPP) (t C·ha⁻¹·year⁻¹) simulations and (*b*) estimations based on remote sensing for the Lake Abitibi Model Forest (kappa value $K = 0.51$). The grid size is 3 km × 3 km. Part (*a*) was based on the TRIPLEX model simulation for 1994 and (*b*) was converted from 1 km × 1 km to 3 km × 3 km using spatial NPP estimates of Liu et al. (2002) for 1994.
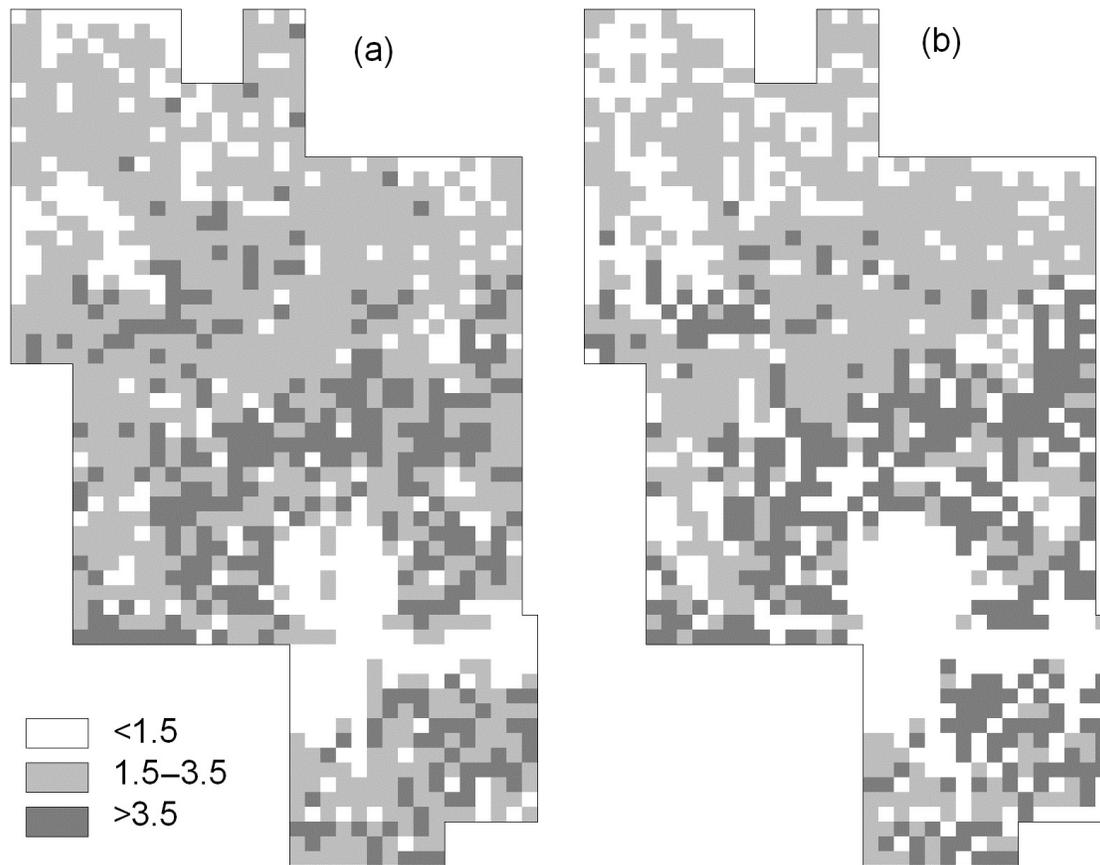
3.9 t C·ha⁻¹·year⁻¹ reported by Gower et al. (1997) for BOREAS in central Canada.

Volume simulation and distribution

The volume simulation covered all 44 343 stands in LAMF. Figure 7*a* illustrates the spatial distribution of simulated volume density that can be used for the assessment of growth and yield in the LAMF. The simulated volume density was higher in Iroquois Falls North than in Iroquois Falls South for black spruce and trembling aspen, but the volume density was slightly higher in Iroquois Falls South for jack pine (Table 3). The simulated average stand volume was around 174 m³·ha⁻¹ for all three species in 2000. The simulated total stocking (total of all the individual stands) was approximately 157 × 10⁶ m³ for 2000.

Figure 8 shows total volumes for the three different species in each age-class. The total volume of forests in the LAMF consisted of about 68% (107 × 10⁶ m³) black spruce, 7% (11 × 10⁶ m³) jack pine, and 13% (21 × 10⁶ m³) trembling aspen. The total volume for each age-class varied but peaked at 70–90 and 130–150 years as of 1995. These two age-classes covered 56% of the total volume in the LAMF. Moreover, 39% of the total volume was distributed in older stands (>100 years). The simulated annual growth rate in the 1990s was approximately 1.3% or 2.06 × 10⁶ m³·year⁻¹ for the entire region. However, the average growth rates in the

LAMF were different in the early and late 1990s. Figure 9 shows that the growth rates of tree height and DBH for most of the age-classes over the period 1996–2000 were greater than those for 1991–1995, particularly for older stands. The average growth rates of tree height and DBH from 1996 to 2000 were about 1.7% and 1.8% higher, respectively, than those for 1991–1995.

Discussion

Statistically speaking, validating a process-based ecological model is a big challenge because of difficulties in obtaining sufficient samples of field measurements. This has limited the application of process-based ecological models, although they have, in theory, a strong long-term forecasting ability under changing climate, soil, and water conditions. The best way to validate a process-based model is to compare model simulation with growth and yield measurements such as PSP measurements (see Fig. 3). Because most data from forest inventories are interpreted from air photos, it implies that interpretation errors could influence the model validation (Fig. 4). We used three data sources in this study in testing model performance and accuracy: field data from traditional growth and yield plots (PSP), forest inventory, and normal yield tables. Our results suggest that the process-based TRIPLEX1.0 produced less bias (about ±4%) comparing simulated height

Fig. 7. The spatial distributions of (*a*) volume density in contrast with (*b*) age-class in the Lake Abitibi Model Forest for the year 2000.
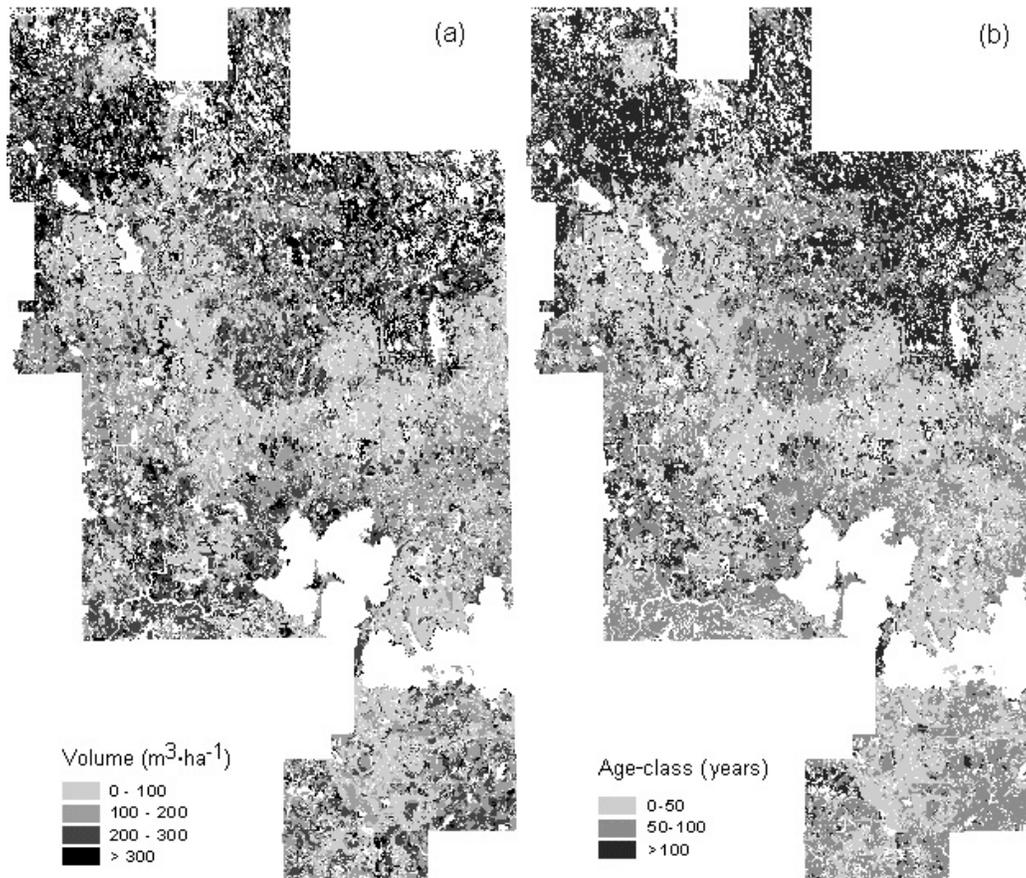
Table 3. The features of spatial distribution for volume density in the Lake Abitibi Model Forest (LAMF), simulated for 2000.

	Black spruce		Jack pine		Trembling aspen		Average[a]	
	N	S	N	S	N	S	N	S
Avg. stand age (year)	80	63	68	54	63	48	77	59
Volume density (m³·ha⁻¹)	160	139	281	282	200	132	176	162
Proportion of total area (in site classes 1 and 2)	81%	94%	78%	95%	92%	94%	83%	88%
Proportion of total area (in site class 3)	19%	6%	22%	5%	8%	6%	17%	12%

Note: N and S denote Iroquois Falls North and Iroquois Falls South, respectively.

[a]Average includes black spruce, jack pine, trembling aspen, and other tree species that occupied 8% of LAMF area.

and DBH with PSP measurements and could produce higher bias (about ±20%) on predicting tree height, DBH, and basal area based on forest inventory and empirical growth curves. Generally, the model parameterization always affects process-based model performance by accumulating errors at each time step. We have found that allocation parameters in the TRIPLEX1.0 model resulted in simulation errors, especially for jack pine and trembling aspen stands. Figures 4*c*, 4*d*, 4*e*, and 4*f* show overestimates in both younger (with lower height) and older (with taller height) stands. This is because too much NPP was partitioned by the TRIPLEX1.0 to stems rather than to foliage and roots for younger and older stands of jack pine and trembling aspen. Unfortunately, the current parameters used for NPP allocation were calibrated for black spruce without the consideration of different site classes. This produced relatively large biases in the estimation of basal area and DBH for trembling aspen site classes 2 and 3

(Tables 1 and 2) and biases of tree height for black spruce site class 3 (Table 2). Battaglia and Sands (1997) also reported that NPP partitioning to stems is dependent on site index in their model simulations for *Eucalyptus globules* in Australia.

To increase model accuracy, the parameterization of NPP allocation needs to be developed for different species and different site classes. Hopefully, such simulation errors can be minimized by improving the NPP allocation algorithm in the TRIPLEX model in the future (X. Zhou, C.H. Peng, and Q.L. Dang, unpublished data). As for testing the accuracy of modeled NPP itself, it should be validated using field NPP measurements. Unfortunately, we were unable to test the modeled NPP directly in the LAMF because the measurements of NPP are not available at the landscape scale. The comparison between modeled spatial NPP and estimated NPP distribution based on remote sensing (Fig. 6) can be a reference

Fig. 8. The estimation of total volume and its distribution over tree age-class in the year 2000 for the Lake Abitibi Model Forest.
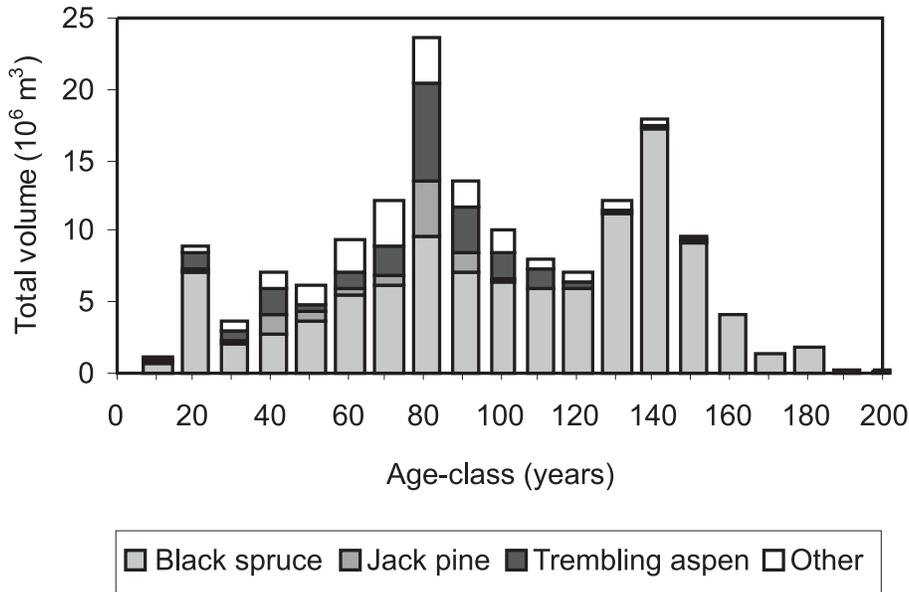
Fig. 9. The temporal variations of increasing rate on (*a*) tree height and (*b*) DBH over age-class in the 1990s for the Lake Abitibi Model Forest. The percentages on the *y*-axis denote growth rate of tree height or DBH for 1991–1995 and 1996–2000.
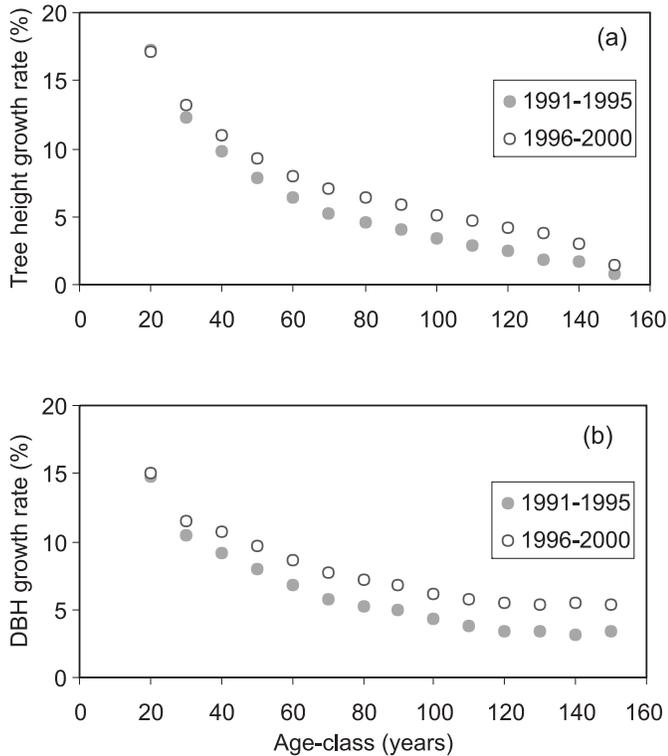
for checking the difference between bottom-up and top-down estimates.

Tree volume distribution is known to depend on tree age, site class, and climate and soil conditions. The simulation results (Fig. 9) show differences in growth rate in different growth periods, which may be indicative of climate effects

(temperature and precipitation) in the 1990s. Corresponding to the increases in growth rates (Fig. 8), there was an increase of 0.4 °C in average annual temperature and an increase of 80 mm in precipitation between the early and late 1990s. Although this discussion supports the hypothesis that climate directly affects tree growth, we cannot provide direct evidence for the change in growth rates from observations because there are no forest growth and yield data available for each year in the LAMF for the 1990s.

The spatial distribution of stand volume density is generally determined by the distribution of stand ages and site classes. In the LAMF, black spruce and trembling aspen stands were generally older in Iroquois Falls North than in Iroquois Falls South, and the corresponding volume density was also higher in Iroquois Falls North (Figs. 7*a* and b, and Table 3). Additionally, the average volume density (Fig. 7*a*) was generally higher in areas of clay soils (Fig. 1). An exception in Table 3 was found for the jack pine site, in which the volume density indicates good growing conditions in the south of the LAMF. Because there are no observed volumes available for every stand, we were unable to compare model simulations with observed volume density at the regional scale. However, we estimated that the average volume was about 174 m^3·ha^{-1} from our model simulation and converted this using the Plonski yield tables to gross merchantable volume with the averaged value of 87 m^3·ha^{-1}, which is in good agreement with the LAMF average volume (86.5 m^3·ha^{-1}). The latter was calculated from annual allowable cut (AAC), estimated as approximately 0.75 × 10^6 m^3 from a total area of 8670 ha (Griffin 2001) in the LAMF.

The total tree volume simulated in this study can also be used as a reference for forest harvest and regeneration planning. According to the current Forest Management Plan of the LAMF, the AAC is reviewed every 5 years and is approximately 0.75 × 10^6 m^3 (Griffin 2001) from 1995 to 2015. This AAC was converted from the AAC area (approximately 8670 ha, 0.11% of the total forest area in the LAMF) described in the Forest Management Plan. Our model simula-

tion results suggest that the current AAC volume was only about 36.4% of the annual volume increment (2.06×10^6 m^3) in the LAMF. The actual annual harvested volume of 0.61×10^6 m^3·year^{-1} between 1990 and 2000, estimated from the data reported by Griffin (2001), presents only about 29.6% of that annual volume increment. This implies that adequate forest productivity with a temperate harvest was helpful for the sustainable management of the LAMF over the past decade.

Conclusions

In summary, this study has demonstrated the feasibility of testing and validating a process-based carbon dynamic model using PSP measurements, forest inventory data, and empirical growth and yield curves. On the other hand, this study has also shown that the TRIPLEX1.0 model can be used to provide growth and yield information to complement empirical growth and yield models for forest management practices. This approach is particularly valuable for areas where there are no or insufficient PSP data available. The simulations of forest growth and yield are in good agreement with field measurements, forest inventory, and normal yield tables for black spruce, jack pine, and trembling aspen. The coefficients of determination (R^2) between modeled values and PSP measures are 0.92 for height and 0.95 for DBH. The TRIPLEX model produced lower biases (about 3.9% for height and 2.1% for DBH) for individual PSPs. At the landscape level, forest inventory data and a normal yield table were used for comparing model predictions. The comparisons showed that the total R^2 ranged from 0.73 to 0.89 for height, 0.72 to 0.85 for DBH, and 0.82 to 0.96 for basal area. However, the simulation biases have significantly increased, ranging from –18.4% to 6.8% for tree height, –7.3% to 17.9% for DBH, and –12.9% to 18.2% for basal area, when the model simulations were scaled up to the landscape level. The total tree volume in the LAMF was estimated to be 157×10^6 m^3 in 2000 (68% black spruce, 7% jack pine, 13% trembling aspen, and 12% others). The total annual volume increment in the LAMF in the 1990s was estimated to be greater than the AAC volume (about 36.4% of the modeled annual increment) and annual actual harvest (about 29.6% of the modeled annual increment) in the 1990s.

Acknowledgements

References

Battaglia, M., and Sands, P.J. 1997. Modelling site productivity of *Eucalyptus globules* in response to climatic and site factors. Aust. J. Plant Physiol. **24**: 831–850.

Battaglia, M., and Sands, P.J. 1998. Process-based forest productivity models and their application in forest management. For. Ecol. Manage. **102**: 13–32.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. For. Res. **31**: 384–391.

Bossel, H. 1991. Modeling forest dynamics: moving from description to explanation. For. Ecol. Manage. **42**: 129–142.

Bossel, H. 1996. TREEDYN3 Forest Simulation Model. Ecol. Model. **90**: 187–227.

CCCma. 2003. The Second Generation Coupled Global Climate Model (CGCM2) data. Meteorological Service of Canada, Environment Canada. Available from http://www.cccma.bc.ec.gc.ca/data/cgcm2/cgcm2.shtml [cited 2 July 2003].

Centre for Land and Biological Resources Research. 1993. Soil carbon data for Canadian soils. CLBRR Contribution No. 92-179. Centre for Land and Biological Resources Research, Ottawa.

Cohen, J. 1960. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. **20**: 37–46.

Elkie, P.C., Towill, W.D., Ride, K.R., and McIllwrath, D.L. 2000. Ontario Land Inventory Primeland/Site Information System (OLIPIS) [online]. Ont. Min. Nat. Resour. Northwest Sci. Technol. Techn. Man. TM-005. Available from http://nwsi.mnr.gov.on.ca/spectrasites/internet/nwsi/media/documents/nwtm005.pdf.

Emanuel, W.R., Shugart, H.H., and Stevenson, M.P. 1985. Climate change and the broad-scale distribution of terrestrial ecosystem complexes. Clim. Change, **7**: 29–43.

Environment Canada. 1994. Canadian monthly climate data and 1961–1990 normals [CD-ROM]. Version 3.0E. Environment Canada, Ottawa.

Environment Canada. 2000. Narrative descriptions of terrestrial ecozones and ecoregions of Canada: Boreal Shield ecozone. Environment Canada, Ottawa.

Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J., and Stow, T.K. 1997. Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. BOREAS special issue. J. Geophys. Res. **102**(24D): 29 029 – 29 041.

Griffin, T. 2001. Lake Abitibi Model Forest local level indicator status report: 2000. Lake Abitibi Model Forest, Cochrane, Ont.

Kimball, J.S., Thornton, P.E., White, M.A., and Running, S.W. 1997. Simulating forest productivity and surface-atmosphere carbon exchange in the BOREAS study region. Tree Physiol. **17**: 589–599.

Kimmins, J.P. 1993. Scientific foundations for the simulation of ecosystem function and management in FORCYTE-11. Can. For. Serv. North. For. Cent. Inf. Rep. NOR-X-328.

Kimmins, J.P., and Scoullar, K.A. 1995. Incorporation of nutrient cycling in the design of sustainable, stand-level, forest management system using the ecosystem management model FORE-CAST and its output format FORTOON. *In* Nutrient uptake and cycling in forest ecosystems. *Edited by* L.O. Nilsson. Ecosystem Res. Rep. No. 13, EUR-15465.

Korol, R.L., Running, S.W., and Milner, K.S. 1994. Incorporating intertree competition into an ecosystem model. Can. J. For. Res. **25**: 413–424.

Kurz, W.A., Apps, M.J., Webb, T.M., and McNamee, P.J. 1992. The carbon budget of the Canadian forest sector: Phase 1. Can. For. Serv. North. For. Cent. Inf. Rep. NOR-X-326.

Landsberg, J.J., and Coops, N.C. 1999. Modeling forest productivity across large areas and long periods. Nat. Res. Model. **12**: 383–411.

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

Liu, J., Peng, C., Dang, Q., Apps, M.J., and Jiang, H. 2002. A component objective model strategy for reusing ecosystem models. Comput. Electr. Agric. **35**: 17–33.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Agren, G.I., Oliver, C.D., and 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.

Milner, K.S., Coble, D.W, McMahan, AJ., and Smith, E.L. 2003. FVSBGC: a hybrid of the physiological model STAND-BGC and the forest vegetation simulator. Can. J. For. Res. **33**: 466–479.

Monserud, R.A. 1990. Methods for comparing global vegetation maps. Working Paper WP-90-40. International Institute of Applied Systems Analysis, Laxenburg, Austria. pp. 5–21.

Neilson, R.P., and Marks, D. 1994. A global perspective of regional vegetation and hydrologic sensitivities from climatic change. J. Veg. Sci. **5**: 715–730.

Newcomer, J., Landis, D., Conrad, S., Curd, S., Huemmrich, K., Knapp, D. et al. 2000. Collected data of the boreal ecosystem–atmosphere study [CD-ROM]. The BOREAS Information System NASA Goddard Space Flight Center, Greenbelt, Md.

Oelschlagel, B. 1995. A method for downscaling global climate model calculation by a statistical weather generator. Ecol. Model. **82**:199–204.

Ontario Ministry of Natural Resources. 1996. Forest resources of Ontario. Ontario Ministry of Natural Resources, Sault Ste. Marie, Ont.

Oak Ridge National Laboratory. 2002. Global soil data products. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Parton, W.J., Schimal, D.S., Cole, C.V., and Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. **51**: 1173–1179.

Parton, W.J., Scurlock, J.M., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S. et al. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. Glob. Biogeochem. Cycles, **7**: 785–809.

Pastor, J., and Post, W.M. 1988. Response of northern forests to CO_2-induced climate change. Nature (London), **334**: 55–58.

Peng, C. 2000. Understanding the role of forest simulation models in sustainable forest management. Environ. Impact Assess. Rev. **20**(4): 481–501.

Peng, C., Apps, M.J., and Price, D.T. 1998. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in central Canada. Glob. Biogeochem. Cycles, **12**: 381–402.

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

Plonski, W.L. 1974. Normal yield tables (metric) for major forest species of Ontario. Division of Forests, Ontario Ministry of Natural Resources, Ottawa, Ont. pp. 4–39.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A., and Solomon, A.M. 1992. A global biome model based on plant physiology and dominance, soil properties and climate. J. Biogeogr. **19**: 117–134.

Running, S.W., and Coughlan, J.C. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and priimary production processes. Ecol. Model. **42**: 125–154.

Ryan, M.G., Lavigne, M.B., and Gower, S.T. 1997. BOREAS special issue. Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate. J. Geophys. Res. **102**(D24): 28 871 – 28 883.

Sands, P.J., Battaglia, M., and Mummery, D. 2000. Application of process-based models to forest management: experience with PROMOD, a sample plantation productivity model. Tree Physiol. **20**: 383–392.

Siltanen, R.M., Apps, M.J., Zoltai, S.C., Mair, R.M., and Strong, W.L. 1997. A soil profile and organic carbon data base for Canadian forest and tundra mineral soils. Northern Forestry Centre, Canadian Forest Service, Edmonton, Alta. pp. 2–50.

Steele, S.J., Gower, S., Vogel, J.G., and Norman, J.M. 1997. Root mass, net primary production and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitoba, Canada. Tree Physiol. **17**: 577–587.

Zhou, X., Peng, C.H., Dang, Q.L., Chen, J., and Parton, S. 2004*a*. Simulating forest growth and carbon dynamics of the Lake Abitibi Model Forest in northeastern Ontario. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, OFRI-REP 163.

Zhou, X., Peng, C., and Dang, Q. 2004*b*. 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.

Appendix A

Appendix appears on the following page.

Table A1. Parameters used in the TRIPLEX1.0 simulations.

Parameter	Description	Note
Tveg = 5	Temperature of vegetation begin and end	Bossel 1996
Sla = 6	Specific leaf area ($m^2 \cdot kg^{-1}$)	Kimball et al. 1997
Topt = 15	Optimum temperature for producing GPP	Kimball et al. 1997
Ccpp = 0.39	Conversion of GPP to NPP	Ryan et al. 1997
Cloud = 0.4	Cloud ratio for a month	Bossel 1996
AlphaC = 0.05	Canopy quantum efficiency	Landsberg and Waring 1997
Lnr = 0.26	Lignin/nitrogen ratio	Parton et al. 1993[a]
K1–K8	Max. decomposition rates in soil	Parton et al. 1993[a]
A1 = 15	Soil water depth of first layer (cm)	Parton et al. 1993[a]
A2 = 15	Soil water depth of second layer (cm)	Parton et al. 1993[a]
A3 = 15	Soil water depth of third layer (cm)	Parton et al. 1993[a]
AWL1 = 0.5	Relative root density in first layer	Parton et al. 1993[a]
AWL2 = 0.3	Relative root density in second layer	Parton et al. 1993[a]
AWL3 = 0.2	Relative root density in third layer	Parton et al. 1993[a]
KF = 0.5	Fraction of H_2O flow to stream	Assumption
KD = 0.5	Fraction of H_2O flow to deep storage	Assumption
KX = 0.3	Fraction of deep storage water to stream	Assumption
CD = 25	Crown to stem diameter ratio	Bossel 1996
AgeMax = 200	Max. tree age to grow	Assumption
MiuNorm = 0.002	Normal mortality (yearly)	Bossel 1996[b]
MiuCrowd = 0.02	Crowding mortality (yearly)	Bossel 1996
GamaR = 0.21	Root loss ratio (yearly)	Steele et al. 1997
MaxGama = 0.01	Max. foliage loss ratio (yearly)	Gower et al. 1997[c]
F_{hdmin} = 110, 140, 130	Min. growth factors (black spruce, jack pine, trembling aspen)	Plonski 1974[d]
F_{hdmax} = 85, 95, 90	Max. growth factors (black spruce, jack pine, trambling aspen)	Plonski 1974[d]

[a]Values are given by CENTURY.
[b]The stand mortality was assumed as the normal mortality (no canopy competition for light) plus crowding mortality.
[c]Estimated based on results (0.069–0.083 year^{-1} in the southern BOREAS area) of Gower et al. (1997).
[d]Estimated based on normal yield table (Plonski 1974).