ECOLOGICAL MODELLING

TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics

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Abstract

To predict the potential effects of future global environmental changes (e.g. climate, land-use, fire disturbance, and forest harvesting) on the sustainability of forest ecosystems, forest resource managers will need forest simulation models. Basic approaches to modelling forest growth and dynamics include the use of empirical, mechanistic, and hybrid forest simulation models. In this paper, a hybrid, monthly time-step model of forest growth and carbon dynamics (TRIPLEX) is described and tested. The TRIPLEX model integrates the forest production model of 3-PG (For. Ecol. Manage. 95 (1997) 209), the forest growth and yield model of TREENYD3 (Ecol. Model. 90 (1996) 187), and the soil–carbon–nitrogen model of CENTURY4.0 (Global Biogeochem. Cycles 7 (1993) 785). The model is intended to be comprehensive without becoming complex, and minimizes the number of input parameters required, while capturing key processes and important interactions between the carbon and nitrogen cycles of forest ecosystems. It is designed as a hybrid of both empirical and mechanistic components that can be used for (1) making forest management decisions (e.g. growth and yield prediction), (2) quantifying forest carbon budgets, and (3) assessing the effects of climate change in both the short and long term. We tested TRIPLEX against age-dependent growth measurements from 12 permanent sample plots (PSP) in jack pine (*Pinus banskiana* Lamb.) stands in northern Ontario (Canada). Comparisons of simulated stand growth variables (e.g. tree diameter, height, and stem density) with those observed in PSPs indicated a good agreement over 30 years. Predictions of tree total volume and aboveground biomass were within the expected range for these plots. While the model is promising, future modifications are discussed. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Sustainable forest management (SFM) represents an important paradigm for forestry. Traditional forestry objectives aimed at sustainable yield management are being replaced with those

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of sustainable ecosystem management (CCFM, 1992; UNCED, 1992). SFM is facing major challenges including (1) sustaining forest ecosystem productivity; (2) improving carbon (C) sequestration potential; and (3) mitigating and adapting to the effects of future climate change. Predicting the potential effects of future changes in global environment (such as climate, land-use, fire disturbance, and forest harvesting) on the sustainability of forest ecosystems will require forest resource managers to make use of forest simulation models (Peng, 2000a). Basic approaches to modelling forest growth and C dynamics include empirical, mechanistic, and hybrid forest simulation models, each with their advantages and limitations (Landsberg, 1986; Kimmins, 1990; Mohren et al., 1994; Landsberg and Coops, 1999; Mäkelä et al., 2000; Peng, 2000a,b).

Empirical models (e.g. forest growth and yield models) are derived from large amounts of field data, and describe growth rate as a regression function of variables such as site index, age, tree density, and basal area. The major strength of the empirical approach is that it describes the best relationship between the measured data and the growth-determining variables using a specified mathematical function or curve. Empirical models require only simple inputs, and can be easily constructed. They are also easily incorporated into diversified management analyses and silvicultural treatments, and efficiently and accurately provide quantitative information for use in forest management planning. They may be an appropriate method for predicting short-term yield for time scales over which historical growth conditions are not expected to change significantly. However, empirical growth and yield models are not robust, for example, for analysing the consequences of climatic changes or environmental stress (Kimmins, 1990; Shugart et al., 1992).

Unlike empirical models, mechanistic process-based models generally describe key ecosystem processes or simulate the dependence of growth on a number of interacting processes, such as photosynthesis, respiration, decomposition, and nutrient cycling. These models offer a framework for testing and generating alternative hypotheses and have the potential to help us accurately describe how these processes will interact under given environmental change (Landsberg and Gower, 1997; Peng, 2000a,b). Consequently, their main advantages are the inclusion of the ecophysiological principles and their long-term forecasting ability within changing environments. Over the last decade, much progress has been made in the development of more mechanistic forest growth models designed to integrate energy, C, nutrient and water cycles. However, few process-based models have been applied in forest management (Korzukhin et al., 1996; Landsberg and Gower, 1997; Sands et al., 2000; Mäkelä et al., 2000).

Recently, Battaglia and Sands (1998), Landsberg and Coops (1999), Mäkelä et al. (2000) and Peng (2000a,b) have extensively discussed the advantages and disadvantages of using empirical and mechanistic process models in SFM. Generally, a weakness of one type of model is strength of the other, and vice versa. It is almost always possible to find an empirical model that provides a better fit for a given set of data due to the constraints imposed by the assumptions of process models. Nevertheless, empirical and process models can be married into hybrid models in which the shortcomings of both approaches can be overcome to some extent. This is the rationale behind the hybrid simulation approach to forest growth and C dynamics modelling (Kimmins, 1993; Battaglia et al., 1999; Kimmins et al., 1999; Peng, 2000b). Specifically, incorporating the key elements of empirical and process approaches into a hybrid ecosystem modelling approach can result in a model that predicts forest growth, production and C dynamics in both the short and long term (Pastor and Post, 1988; Battaglia and Sands, 1998; Kimmins et al., 1999).

In this paper, a hybrid, monthly time-step model of forest growth and C and nitrogen (N) dynamics is presented. The TRIPLEX model, developed based on three well-established process models, i.e. 3-PG (Landsberg and Waring, 1997), TREEDYN3.0 (Bossel, 1996), and CENTURY4.0 (Parton et al., 1993), combines empirical and mechanistic components that can be used for (a) making forest management decisions (e.g. growth and yield prediction), (b) quantifying forest carbon budgets, and (c) assessing the effects

of climate change on forests. The objectives of this paper are to (1) document the scientific foundation, major assumptions, and mathematical formulation of the TRIPLEX model, (2) demonstrate its predictive ability by presenting model testing and sensitivity analysis results, and (3) discuss the future model improvements.

2. Model structure

Although much progress has been made in the past decade in the development of more mechanistic forest growth models that can integrate energy, carbon, nutrient and water cycles (Mäkelä et al., 2000), the existing models have some shortcomings for predicting forest growth and carbon dynamics. For example, the 3-PG (Physiological Principles in Predicting Growth) is a simplified process-based model that is designed to predict the growth, diameter distribution, and annual mortality for individual forest stands (Landsberg and Waring, 1997). However, the model does not include a soil component or feedbacks between the aboveground and belowground. TREEDYN3 (Bossel, 1996) has dynamic module for forest growth and yield, but has a simple soil decomposition sub-model (with only one soil carbon pool) and shares similar shortcomings with 3-PG. It does not take into account the effects of soil water on soil decomposition. Although CENTURY has simple and empirical aboveground processes and no forest growth and yield module, it does include a robust soil sub-model and climatic variables. In addition, 3-PG, TREEDYN3, and CENTURY4.0 have similar sub-models and same monthly time step for simulation that were easily integrated into TRIPLEX as model components.

TRIPLEX, like the 3-PG model (Landsberg and Waring, 1997), is intended to bridge the gap between empirical forest growth and yield and process-based C balance models. It is comprehensive without being complex, and minimizes the number of input parameters required, while capturing well-understood key forest growth-determining processes and important interactions among the C, N, and water cycles of complex forest ecosystems. In addition, TRIPLEX simu-

lates average stand characteristics rather than those of individual trees. It is designed to develop as a generic model that can be parameterized for even- or uneven-age coniferous and broad-leaved species at any geographical location and for different soil and climate conditions. As shown in Fig. 1, TRIPLEX has four major sub-models: (1) A forest production sub-model that estimates photosynthetically active radiation (PAR), gross primary productivity (GPP), and above- and belowground biomass; (2) A soil C and N sub-model that simulates C and N dynamics in soil and litter pools; (3) A forest growth and yield sub-model that calculates tree growth and yield variables, including height, diameter, basal area and volume; and (4) A simple soil water balance sub-model that simulates water dynamics. Model components are presented by class objects using an objective-oriented programming (C + +) approach. The model uses a monthly time step and is driven by monthly weather data. Key features and modelling processes of TRIPLEX are presented in Tables 1 and 2, respectively.

3. Sub-model descriptions

In general, forest growth and C and N dynamics described in TRIPLEX model are primarily driven by solar radiation. Both environmental conditions (e.g. temperature, precipitation, soil water and N) and biological factors (e.g. forest age, biomass allocation, tree form, mortality) modify actual forest growth and C and N fluxes (Fig. 1). Major equations in TRIPLEX are presented below (Table 3).

3.1. Photosynthetically active radiation (PAR)

PAR is calculated based on the equations given in TREEDYN3 (Bossel, 1996), where the initial PAR (I_{0PAR}) was computed as a function of solar constant (= 1360 W m^{-2}), solar radiation fraction ($\varphi_{PAR} = 0.47$), solar height (sin β), and light absorption based on solar height and atmospheric absorption factor K_{atm} (Penning de Vries and van Laar, 1982; Richter, 1985):

$$I_{0PAR} = 1360\varphi_{PAR}\sin(\beta)e^{-\frac{K_{atm}}{\sin(\beta)}} \qquad (1)$$

This PAR calculation can be used for regional PAR simulations because solar height ($\sin\beta$) is calculated as a function of latitude and time of day. The time step used for PAR is 0.1 h.

Monthly canopy received PAR (I_m) is estimated from a 'mixture' of monthly PAR under both clear sky (I_{mclr}) and cloudy sky (I_{mcld}). The PAR of a cloudy day is assumed to be 20% of that of clear sky for the same day (Penning de Vries and van Laar, 1982, p. 103). This distinction can reduce the bias produced using an average radiation value because the photosensitivity curve is naturally nonlinear (Bossel, 1996). A cloud factor (C_{cld}) is used by Bossel (1996) to calculate monthly PAR. The value of C_{cld} is determined using the assumption that the annual sum of radiation under clear and cloudy sky is equal to the observed total annual radiation (Bossel, 1996). Thus, monthly canopy PAR is calculated as:

$$I_m = (1 - C_{cld})I_{mclr} + C_{cld}I_{mcld} \qquad (2)$$

3.2. Gross primary productivity

We adapted the simplified process-based productivity model of 3-PG developed by Landsberg and Waring (1997) to calculate GPP (in t ha^{-1}) and net primary productivity (NPP, in t ha^{-1}). The total carbon gain (GPP) in a month is calculated as a function of monthly received PAR (I_m) modified by leaf area index (LAI), forest age (f_a), monthly mean air temperature (f_t), soil drought (f_w), and percentage of frost days in a month (f_d); k is a conversion constant.

$$GPP = kI_m LAI f_a f_t f_w f_d \qquad (3)$$

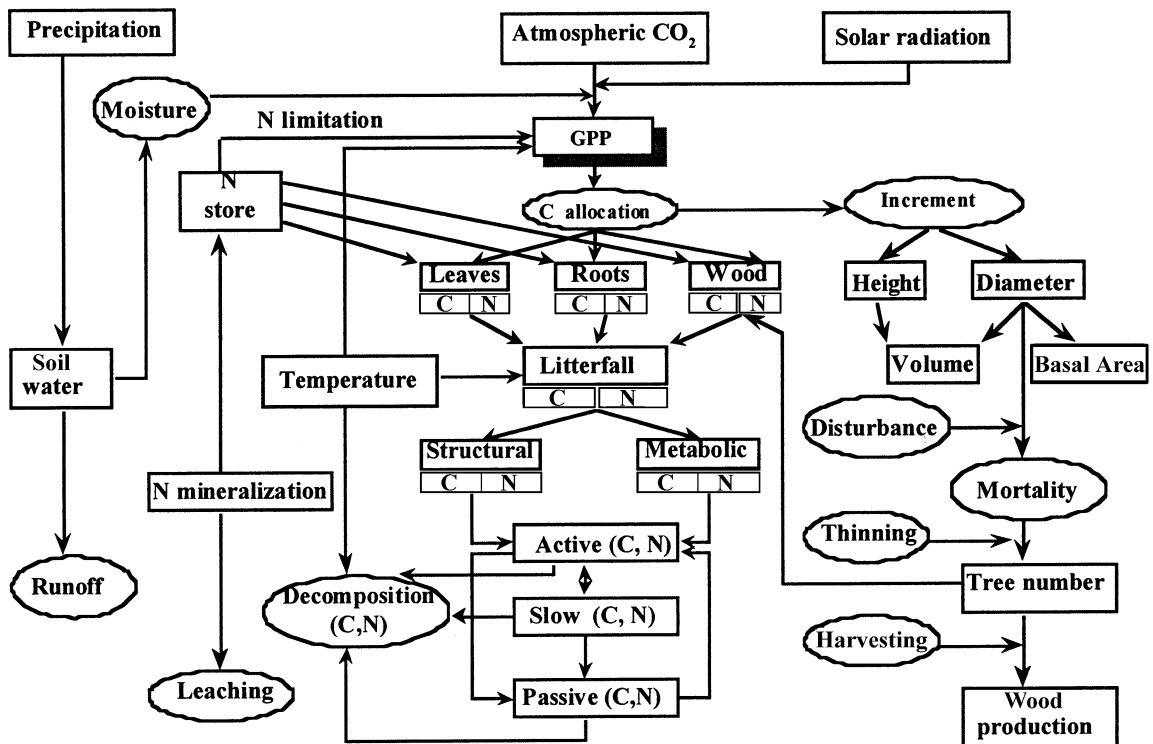Calculation of f_a, f_t, and f_w are as follows:

Fig. 1. Flow diagram showing the key pools and fluxes of carbon, nitrogen, and water between the forest ecosystem and external environment in TRIPLEX 1.0. Rectangles represent pools or state variables. Ovals represent simulated processes. Arrows refer to carbon (C), nitrogen (N) and water flows. GPP is gross primary productivity.

Table 1
Key features of the TRILEX model

Driving variables (inputs)	Monthly climate data (e.g. mean, maximum and minimum temperature, total precipitation, cloud); atmospheric CO_2 concentration; nitrogen deposition and fixation rate
Forest growth	Process-based tree growth and geometric calculation
Mass balances	Carbon, nitrogen, and water pools and fluxes fully balanced
Integration	Matter and energy coupled, empirical and mechanistic processes hybridizing
Modelling strategy	Use objective-oriented programming (OOP) approach. Model component is presented by class object, allowing easy maintenance and development
Operation (time step)	Monthly carbon flux and allocation calculation; annual tree growth, carbon, nitrogen, and water budget
Outputs	Tree diameter, height, basal area, volume; leaf area index; NPP; biomass; soil C, N and water dynamics
Constrains	Both empirical and fundamental ecophysiological relationship and parameters
Development potential	From stand to ecosystem, and landscape levels; can be linked with GIS and remote sensing

$$f_a = \frac{1}{1 + \left(\dfrac{F_{ar}}{0.95}\right)^3} \tag{4}$$

$$f_t = \left(\frac{T_a - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_a}{T_{max} - T_{opt}}\right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}\right)} \tag{5}$$

$$f_w = \min\left(e^{p_{cof}VPD}, \frac{1}{1 + \left(\dfrac{1 - W_r}{W_c}\right)^{W_p}}\right) \tag{6}$$

where T_a, T_{min}, T_{max}, and T_{opt} are the monthly mean air temperature, minimum, maximum and optimum temperature for tree growth, respectively; F_{ar}, VPD, and p_{cof} are the relative forest age, vapour pressure deficit, and coefficient for VPD; and W_c and W_p are constants related to soil types. W_r is the soil moisture ratio described by Eq. (31) (see Section 3.6).

In 3-PG, relative forest age (F_{ar}) is the ratio of the actual forest age to the maximum forest age. The age effect Eq. (4) implies that younger forests have higher growth efficiencies. This greatly overestimates the growth of young forest stands when applied to Canadian boreal forests. Thus, we modified F_{ar} and f_a to be:

Table 2
Major processes represented in TRIPLEX, modeling approaches, and original sources

Process	Approach	Sources
Photosynthetically active radiation (PAR)	Calculated as function of latitude and time (Eq. (1) and Eq. (2))	TREEDYN3 (Bossel, 1996)
Gross primary productivity (GPP)	Calculated as function of PAR and the effects of biotic and abiotic factors (Eq. (3))	3-PG (Landsberg and Waring, 1997)
Net primary productivity (NPP)	Calculated as a constant ratio of GPP (Eq. (9))	3-PG (Landsberg and Waring, 1997)
Carbon allocation	Fixed ratio for foliage, root and wood (Eqs. (12)–(15))	3-PG (Landsberg and Waring, 1997)
Tree growth (DBH, H and volume)	Fixed height/diameter allometry and form factors (Eqs. (16)–(18))	TREEDYN3 (Bossel, 1996)
Tree mortality	Tree mortality rate is estimated based on canopy competition for light	TREEDYN3 (Bossel, 1996)
Decomposition	CENTURY model, empirical	CENTURY4.0 (Parton et al., 1993)
Soil C and N	Including structural, metabolic, and active, slow and passive pools	CENTURY4.0 (Parton et al., 1993)
Soil water	CENTURY water balance submodel	CENTURY4.0 (Parton et al., 1993)

Table 3
List of parameters, variables, and constant values used in TRIPLEX

Symbol	Definition	Units	Values
A	Forest age	year	
B_{max}	Maximum C:N ratio of photosynthesis products	–	
B_s, B_t	C:N ratios for sources and target carbon pools	–	
C_i	Amount of carbon for a particular soil carbon pool	$g\,m^{-2}$	
C_{NPP}	A constant ratio of NPP/GPP	–	0.47 ± 0.04[a]
E	Water evaporation	cm	
f_a	Modifier of stand age	–	[0, 1]
f_t	Modifier of temperature	–	[0, 1]
f_d	Modifier of frost day	–	[0, 1]
f_r	Modifier of nitrogen availability	–	[0, 1]
f_w	Modifier soil water on forest growth	–	[0, 1]
F_{ar}	Relative stand age (actual age/estimated maximum age)	–	
F_{amax}	Maximum forest age	year	200[b]
F_{hd}	Tree growth factor based on tree crown competition	–	[0, 1]
F_{hdmni}, F_{hdmax}	Minimum and maximum tree growth factor	–	0, 1
F_{LN}	Modifier of leaching nitrogen	–	
F_{prn}, F_{pra}	Different coefficients for NPP allocation to foliage	–	2.235, 0.006[a]
G	Annual increment of stem wood biomass	$t\,year^{-1}\,ha^{-1}$	
I_m	Actual monthly photosynthetically active radiation	$W\,m^{-2}$	
I_{mcld}	Photosynthetically active radiation under cloudy sky	$W\,m^{-2}$	
I_{mclr}	Photosynthetically active radiation under clear sky	$W\,m^{-2}$	
L	Leached water	cm	
L_B	Total living tree biomass	$t\,ha^{-1}$	
L_N	Soil mineral nitrogen	$g\,m^{-2}$	
LAI	Leaf area index	–	
L_{wi}	Soil water content for a particular soil layer i	cm	
k	Combination of conversion constant	–	
K_i	Maximum decomposition rate	$g\,m^{-2}\,month^{-1}$	0.045–18.5[c]
K_{atm}	Atmospheric absorption factor	–	0.15[d]
M_d	Effect of soil moisture on soil decomposition	–	
N_{avl}	Available nitrogen for plant growth	$g\,m^{-2}\,month^{-1}$	
N_L	Nitrogen leaching	$g\,m^{-2}\,mo^{-1}$	
p	Proportion of decomposed carbon that flows to other C pools	–	
P_N	Plant stored nitrogen	$g\,m^{-2}$	
T	Water transpiration	cm	
T_a	Monthly mean air temperature	°C	
T_d	Effect of soil temperature on soil decomposition	–	[0, 1]
T_{min}	Minimum temperature for tree growth	°C	7[b]
T_{max}	Maximum temperature for tree growth	°C	30[b]
T_s	Soil temperature	°C	
T_{opt}	Optimum temperature for tree growth	°C	
R	Rain fall (precipitation)	cm	
R_e	Decomposition that flows into soil mineral N pool	–	
R_d	Annual increment of individual tree diameter	cm	
R_h	Annual increment of individual tree height	m	
R_I	Soil carbon decomposition rate	$g\,m^{-2}\,month^{-1}$	
R_p	Number of dead trees	$tree\,ha^{-1}\,year^{-1}$	
S_{Fi}	Maximum water holding capacity of soil layer i	cm	8[c]
S_N	Soil mineral nitrogen	$g\,m^{-2}$	
S_{tc}	Tree competition factor based on crown-stem diameter ratio	–	
S_{prn}, S_{pra}	Coefficients for NPP allocation to stems	–	3.3, 0.000006[a]
S_{sand}	Soil sand content	%	

Table 3 (continued)

Symbol	Definition	Units	Values
S_{wl}	Soil water leaching intensity	cm month^{-1}	
p_{cof}	Empirical coefficient for vapour pressure deficiency	–	-0.05[a]
VPD	Vapour pressure deficiency	mb	
W_c, W_p	Constants for calculating soil water, depending on soil types	–	0.5, 5[a]
W_r	Soil moisture ratio	%	
W_s	Soil water content	%	
Ya	Accumulated years from the beginning of competition	year	3[b]
η_r, η_s, η_f	Allocation ratios for root, stem, and foliage	–	
φ	Tree form factor	–	0.4[d]
φ_{PAR}	Solar radiation fraction	–	
γ	Wood density	t C m^{-3}	0.22[e]
$\sin\beta$	Solar height	–	
μ_c	Tree mortality under competition	%	
μ_n	Tree mortality under no competition	%	

[a] Landsberg and Waring (1997).
[b] This study.
[c] Parton et al. (1993).
[d] Bossel (1996).
[e] Alemdag (1984).

$$F_{ar} = \max\left(0, \frac{A - 0.2F_{amax}}{F_{amax}}\right) \tag{7}$$

$$f_a = 0.7 + 0.3\left(\frac{A}{0.2F_{amax}}\right) \quad \text{if } (A < 0.2F_{amax})$$

$$f_a = \frac{1}{1 + \left(\dfrac{F_{ar}}{0.95}\right)^3} \quad \text{if } (A \geq 0.2F_{amax}) \tag{8}$$

where A is forest age, and F_{amax} is maximum forest age. Eq. (8) delays the age effect to juvenile trees, implying that they are more vigorous than young trees, which is more realistic for boreal forests.

An estimation of NPP for a wide range of forests is approximately a fixed fraction of GPP ($C_{NPP} = 0.47 \pm 0.04$; Waring et al., 1998), or:

$$NPP = C_{NPP}GPP \tag{9}$$

The advantage of using a constant ratio of NPP/GPP here is to reduce the difficulty of estimating NPP from GPP based on carbohydrate allocation. Landsberg and Waring (1997) and Waring et al. (1998) argued that the errors resulting from the simplification of carbohydrate allocation are smaller than errors resulting from attempts to calculate respiration of stands growing under a range of environmental conditions. Recent studies also suggested that a constant NPP/GPP ratio may not be affected by an increased temperature and elevated CO_2 concentration (Gifford, 1995; Dewar et al., 1999; Tjoelker et al., 1999; Cheng et al., 2000). In this model, respiration rate is estimated as a constant fraction of photosynthetic C gain, which is similar to calculations used in the GenW model of Kirschbaum (1999).

Actual NPP is most likely lower than potential NPP when nutrient (f_r) limitations are taken into account. In 3-PG, f_r is set to a constant and only affects growth allocation to roots. We modified f_r to be a function of available N (N_{avl}), potential NPP, and maximum C:N ratio (B_{max}) of photosynthesis products, which changes the NPP calculation to:

$$NPP' = C_{NPP}f_rGPP \tag{10}$$

where

$$f_r = \min\left(1.0, \frac{N_{avl}}{\left(\dfrac{NPP}{B_{max}}\right)}\right) \tag{11}$$

3.3. Carbon allocation

Carbon allocation is generally defined as the apportionment of C assimilates among plant parts (Cannell and Dewar, 1994). Although progress in quantifying the carbon allocation for individual trees has been made, mechanisms for determining the amount of C allocated to individual parts of a tree are still poorly understood (Thornley, 1972a,b; Ågren, 1983; Ågren and Ingestad, 1987; Ågren and Wikström, 1993; Valentine, 1985; Landsberg, 1986; Cannell and Dewar, 1994; Bartelink, 1998). We adapted the carbon allocation sub-model of 3-PG for determining the allocation of C to foliage and stems after removing the fraction of total NPP allocated to roots, determined from an evaluation of constraints of photosynthesis and inherent soil fertility.

In 3-PG, the ratio the foliage and stem (P_{fs}) of growth rates is calculated as a function of tree diameter at breast height (D) and constants (F_{prn}, F_{pra}, S_{prn}, S_{pra}):

$$p_{fs} = \frac{F_{prn}F_{pra}}{S_{prn}S_{pra}} D^{(F_{prn} - S_{prn})} \tag{12}$$

where F_{prn} and F_{pra} are empirical coefficients of NPP allocation to foliage, S_{prn} and S_{pra} are empirical coefficients of NPP allocation to stem. Allocation ratios for root (η_r), stem (η_s) and foliage (η_f) are calculated as:

$$\eta_r = \frac{0.5}{1 + 2.5 f_r f_a f_t f_w f_d} \tag{13}$$

$$\eta_s = \frac{1 - \eta_r}{1 + p_{fs}} \tag{14}$$

$$\eta_f = 1 - \eta_r - \eta_s \tag{15}$$

Litterfall ratios of foliage, stem, and root are constants in TRIPLEX as in 3-PG.

3.4. Tree height, diameter, volume and mortality

Individual tree height and diameter increments are calculated from stem wood mass increment based on the approach used in TREEDYN3 (Bossel, 1996). Annual increments of individual tree height (R_h) (in m) and diameter (R_d) (in cm) are calculated using functions as follows:

$$R_d = \frac{4G}{\pi \varphi D^2 \left(2\dfrac{H}{D} + F_{hd} \right)} \tag{16}$$

$$R_h = F_{hd} R_d \tag{17}$$

where G is stem wood biomass increment, which is a representation of tree diameter at breast height (D) and height (H) increment, φ is tree form factor, and γ is wood density (originally assumed to be a fixed constant for a given tree species). We used $\gamma = 0.22$ t C m^{-3} for the jack pine stand (Alemdag, 1984).

Height and diameter growth are influenced by a combination of physiological and morphological responses to environmental factors (Mustard and Harper, 1998; Makinen, 1998; Wang, 1998). The height to diameter ratio has been proposed as an alternative competition index to be used in determining the vigour and 'free growth' status of tree (Mustard and Harper, 1998; Opio et al., 2000). Following the approach of Bossel (1996), we calculate height (H) and diameter (D) growth based on the assumptions: (1) If crown competition ($S_{tc} \geq 1$) is occurring, trees grow more in height; (2) If no competition ($S_{tc} < 1$) is occurring, trees grow more in diameter.

The F_{hd} growth factor (Eq. (17)) that determines where and how much trees grow in D or H is calculated as follows:

1. if ($S_{tc} < 1$ and $H/D \geq F_{hdmin}$), then $F_{hd} = F_{hdmin}$;
2. if ($S_{tc} \geq 1$ and $H/D \leq F_{hdmax}$), then $F_{hd} = F_{hdmax}$;
3. if ($S_{tc} \geq 1$ and $H/D \leq F_{hdmax}$ and $A < 0.5F_{amax}$), then $F_{hd} = F_{hdmin}$;
4. if ($H/D < F_{hdmin}$), then $F_{hd} = F_{hdmax}$;
5. if ($H/D > F_{hdmax}$), then $F_{hd} = 0.5F_{hdmin}$;
6. if ($A > 0.7F_{amax}$), then $F_{hd} = 0$.

where S_{tc} is the tree competition factor described by Eq. (21), and F_{hdmax} and F_{hdmin} are maximum and minimum height-to-diameter ratios (H/D).

Individual tree volume (V) (in m^{-3}) is calculated as a function of H, D and form factor (φ):

$$V = \frac{\pi}{4} D^2 H \varphi \tag{18}$$

The C mass of an individual tree (G_t) (in t C) is estimated as a product of tree volume and the specific wood C density (γ):

$$G_{\mathrm{t}} = \gamma V \qquad (19)$$

In TREEDYN3, tree mortality (μ) is separated into mortality with (μ_{c}) and without (μ_{n}) competition:

$$\mu = \mu_{\mathrm{n}} + \mu_{\mathrm{c}} \qquad (20)$$

μ_{c} and μ_{n} are set as constant values. When there is no competition, μ_{c} is set to zero. When the model is run, every year a proportion of tree stems and biomass are deducted from living trees based on μ.

Tree competition (S_{tc}) is described as relative crown coverage of the stand (m^2 ha^{-1}), which is determined using crown-to-stem diameter ratio (λ_{C}), diameter (D), and stem density (P):

$$S_{\mathrm{tc}} = \frac{\frac{\pi}{4}(\lambda_{\mathrm{C}}D)^2 P}{10\,000} \qquad (21)$$

Competition is assumed to be occurring if $S_{\mathrm{tc}} \geqslant 1$ (details are given in Bossel (1996)).

Sometimes the constant μ_{c} is too small in the early years of stand establishment, but is too high in later stages of stand development. By simplifying increase μ_{c}, an uneven decrease in tree mortality occurs. In TRIPLEX, we calculated μ_{c} to make it bigger in the early years of competition after stand establishment and less later on. Thus, it is calculated as:

$$\mu_{\mathrm{c}}' = \left(1 - \frac{2}{(\mathrm{ya}+1)^2}\right)\mu_{\mathrm{c}} \quad \text{if } (1 < \mathrm{ya} \leqslant 3)$$

$$\mu_{\mathrm{c}}' = \frac{1}{\sqrt{(\mathrm{ya}-2)}}\,\mu_{\mathrm{c}} \quad \text{if } (\mathrm{ya} > 3) \qquad (22)$$

where ya is the accumulated years from the beginning of competition.

In TREEDYN 3, the number of dead trees (R_{p}) each year is calculated as the product of mortality rate (μ) and available tree stem density (P):

$$R_{\mathrm{p}} = -P\mu \qquad (23)$$

In TRIPLEX, living biomass loss (e.g. leaves, branches, stems, roots) due to mortality is calculated differently. TRIPLEX assumes that the probability of death for smaller trees is larger than that for large trees under competition. Thus, biomass loss (W_{loss}) is calculated as following:

$$W_{\mathrm{loss}} = b\left(\frac{R_{\mathrm{P}}}{P}\right)L_{\mathrm{B}} \qquad (24)$$

where b is a constant parameter (< 1.0) and L_{B} is the total living tree biomass.

3.5. Soil carbon and nitrogen dynamics

Friend et al. (1997) investigated several approaches to predicting soil carbon and nitrogen dynamics in Hybrid v3.0, including those described by Thornley and Verberne (1989) and Raich et al. (1991). They concluded that the CENTURY model (Parton et al., 1987, 1993) was the best for simulating soil C and N dynamics. CENTURY can be used for a wide range of litter input rates and soil and climate conditions without requiring detailed parameterization of microbial kinetics as in Thornley and Verberne's (1989) model or different parameterization for different vegetation types as required by Raich et al.'s (1991) model. The soil C–N sub-model of CENTURY has been fully or partly incorporated into other ecosystem models (e.g. G'DAY, Comins and McMurtrie, 1993; Hybrid v.3.0, Friend et al., 1997; GenW, Kirschbaum, 1999; InTEC, Chen et al., 2000). The main part of CENTURY's soil decomposition sub-model was integrated into TRIPLEX because it provides reasonable estimates of both soil C and N mineralization rates (Peng et al., 1998).

In CENTURY, the rate of soil C decomposition for each pool (R_i) is expressed as:

$$R_i = K_i\,C_i\,M_{\mathrm{d}}\,T_{\mathrm{d}} \qquad (25)$$

where i refers to different carbon pools, C_i is the C stock for a particular pool, K_i is the maximum decomposition rate, and M_{d} and T_{d} are the effects of soil moisture and temperature on decomposition, which are calculated as:

$$M_{\mathrm{d}} = \frac{1}{1 + 4\mathrm{e}^{-6W_{\mathrm{s}}}} \qquad (26\mathrm{a})$$

$$T_{\mathrm{d}} = 0.125\mathrm{e}^{\,0.07T_{\mathrm{s}}} \qquad (26\mathrm{b})$$

where T_{s} is the soil temperature (°C) and W_{s} is the soil water content (%).

We extended Eq. (25) by considering limitations of available soil mineral N. To advoid the negative storage of soil mineral N, TRIPLEX uses the following equation to restrict the calculation of actual soil C decomposition:

$$R'_i = \min\left(R_i, \frac{k_i S_N (B_s B_t)}{(p B_s - p B_t - (1-p) B_t R_e)} \right) \qquad (27)$$

where p is the proportion of decomposed C that flows to other C pools, S_N is soil mineral N, R_e is the fraction of released soil organic N generated by soil C decomposition that flows into the soil mineral N pool, and B_s and B_t represent the C:N ratios for source and target C pools, respectively.

In addition, one key simplification that was incorporated into the soil decomposition sub-model in TRIPLEX is time step. TRIPLEX uses a monthly time step while CENTURY uses an internal iteration time step that is less than one month. In CENTURY, N leaching (N_L) is calculated as the product of soil mineral N (S_N) and the amount of water leached. We added an N leaching factor ($F_{IN} = 0.2$) to the function used in CENTURY to constrain unrealistic loss of soil N associated with an increasing rainfall in the simplified soil layer in TRIPLEX:

$$N_L = (0.2 + 0.7 S_{sand}) S_N S_{wl} F_{IN} \qquad (28)$$

where S_{sand} is the soil sand content and S_{wl} is soil water leaching intensity.

Total N available for tree growth (N_{avl}) includes N fixed by plants ($= 0.0005$ NPP), N storaged by plants (P_N), and soil mineral N (S_N). S_N is modified by an empirical availability factor ($K_a = 0.6$), because only a proportion of soil mineral N (excluding leached N) is used for plant growth:

$$N_{avl} = K_a S_N + P_N + 0.0005 \text{NPP} \qquad (29)$$

3.6. Soil water balance

We did not modify CENTURY's soil water sub-model for TRIPLEX. CENTURY uses a simplified water budget model that calculates monthly water loss through transpiration and evaporation, water content of soil, and snow water content (Parton et al., 1987, 1993). Monthly precipitation occurs as snow when the mean air temperature is less than 0 °C. The water balance (L_w) (cm) is calculated as a function of water inputs and outputs:

$$\Delta L_w = R - T - E - L \qquad (30)$$

where R is rainfall (cm), T is transpiration (cm), E is evaporation (cm), and L is leached water (cm).

Hence, soil moisture ratio (W_r) needed for GPP Eq. (7) can be calculated as a function of soil water content of each soil layer (L_{wi}) and the maximum water holding capacity of each layer (S_{Fi}):

$$W_r = \frac{\sum L_{wi}}{\sum S_{Fi}} \qquad (31)$$

where i ($i = 1, 2, 3$) denotes the number of soil layers used to calculate the soil water balance in TRIPLEX.

4. An object-oriented model building strategy

Most existing models and their components are not readily available for reuse because of the problems of input/output compatibility and the process of linkage. Three essential requirements are needed for model reuse. First, components should use the same unit system. For example, 3-PG and TREEDYN3 use the unit of Mg ha^{-1} for dry biomass and mm for precipitation while CENTURY 4.0 uses gm^{-2} and cm. If the unit system were not modified, these models could not work together. Second, a data exchange unit is required to help model components to receive input and send output data correctly and effectively. In TRIPLEX, this data exchange unit is presented as the *InfoCentre*. Finally, an assembling system is required to make it possible for the user to customize models. In TRIPLEX, this assembling system is referred to as the *application interface*.

Table 4
TRIPLEX classes and their major input/output

Class name	Members	Major input	Major output	Origin
Ecosystem	Protected	None	None	N/A
InfoCentre	Public	Climate, site condition	All outputs	N/A
PAR_TD3	Private	Latitude	Radiation	TREEDYN3[a]
DHV_TD3	Private	NPP	DBH, H, V, N	TREEDYN3[a]
GppMaker_3PG	Private	Climate, soil condition	GPP	3-PG[b]
Partitioner_3PG	Private	GPP	Leaf, root, stem	3-PG[b]
DHV_3PG	Private	Biomass	DBH, N	3-PG[b]
GppMaker_Century	Private	Climate, max GPP	GPP	CENTURY4.0[c]
Partitioner_Century	Private	GPP	Leaf, root, stem	CENTURY4.0[c]
SoilWater_Century	Private	Precipitation	Soil water	CENTURY4.0[c]
SoilCN_Century	Private	Litter fall	Soil C, N	CENTURY4.0[c]

NPP: net primary production; GPP: gross primary production; DBH: diameter at breast height; C: carbon; N: nitrogen; H: height; V: volume.

[a] Bossel (1996).
[b] Landsberg and Waring (1997).
[c] Parton et al. (1993).

4.1. Class definitions of model components

TRIPLEX was coded in Borland C++ Builder. It reuses sub-models from 3-PG, TREE-DYN3, and CENTURY4.0, which were originally coded in BASIC, PASCAL and FORTRAN, respectively. All the components are built as class objects developed through the object-oriented programming (OOP) approach. TRIPLEX has 8 classes that control data flow and parameter settings and 11 classes that are related to the simulation of ecological processes. Table 4 shows the 11 simulation classes and their major features.

Ecosystem is a base class for all simulation model components. It declares the basic members of a real ecosystem, such as *Radiation*, *Leaf*, *SoilWater*, and *AvailableN*, as well as basic member functions, such as *Initialize*(), *GetInfo*(), *Simulate*(), *and SetInfo*(). Some common functions are also declared and defined in the base class, for instance, the *clip3*(), which can choose a middle value among three variables.

Actual simulation components (classes) are descendants of Ecosystem but have more variables specific to them and have their inherited member functions defined. For example, Fa is a private member that appears only in the class *GppMaker-3PG*, which represents an age factor in the GPP

calculation, and *GetInfo*() of class *GppMaker-3PG* is an inherited public member function that can get climate data for simulation. *The GetInfo*() function inherited by other classes performs other data work.

The special class *InfoCentre* is designed for model initialization and data exchange. Most of the members of *InfoCentre* have their identical members (variables) in the actual simulation model classes (components) because simulation components need to get and set variable values dynamically with *InfoCentre*. These members in the *InfoCentre* must be declared as public.

4.2. InfoCentre

The InfoCentre of TRIPLEX provides a simple way of data exchange. Each model component will obtain a special pointer to *InfoCentre* for dynamic data exchange and they interact only with the *InfoCentre*. Direct interactions among model components are avoided. The TRIPLEX's *InfoCentre* can function simply i.e. perform only initialization. If the user wants the *InfoCentre* to provide not only a public data exchange area but also services such as selecting or filtering specific information, then more member functions will be needed. The unit conversion is processed before

data goes into the *InfoCentre*. It is done in the *GetInfo*() and *SetInfo*() functions of each component.

5. Model calibration and testing

5.1. Site information

Jack pine (*Pinus banskiana* Lamb.) currently represents more than 35% of the total softwood timber volume in Ontario (OMNR, 1996). About 50% of the jack pine resource in northern Ontario occurs in stands older than 80 years of age. The data set used in model testing was selected from 12 permanent sample plots (PSPs) established and measured by Kimberly Clark Limited between 1950 and 1980s in northern Ontario. This data set contains information on the time of plot establishment and associated soil information (Woods and Miller, 1998). Tree density establishment was not recorded, but had to be reconstructed using an iterative calibration process. This process required multiple interactions of modifications to the initial tree density for all 12 plots until the tree density simulated by TRIPLEX agreed with the measured tree density (Table 5).

In this study, tree stem number, diameter, height, and volume data measured from 12 jack pine PSPs (with exclusion of first measurements) were used to test the predictive ability of TRIPLEX. Averaged climate data (e.g. monthly mean, minimum, and maximum air temperature) collected by the Atmospheric Environment Service (AES, 1983) between 1970 and 1980 were repeatly used over the period of forest growth simulations. Additional information is presented in Table 5.

5.2. Testing runs

We compared the predictions made by TRIPLEX against age-dependent observations to test the prediction ability and behaviours of the model, and to identify its strengths and weaknesses.

5.2.1. Height and diameter

Tree height (H) and diameter at breast height (DBH) are essential forest inventory measurements for estimating timber volume and are also important variables in forest growth and yield modelling. Comparisons of H and DBH predicted
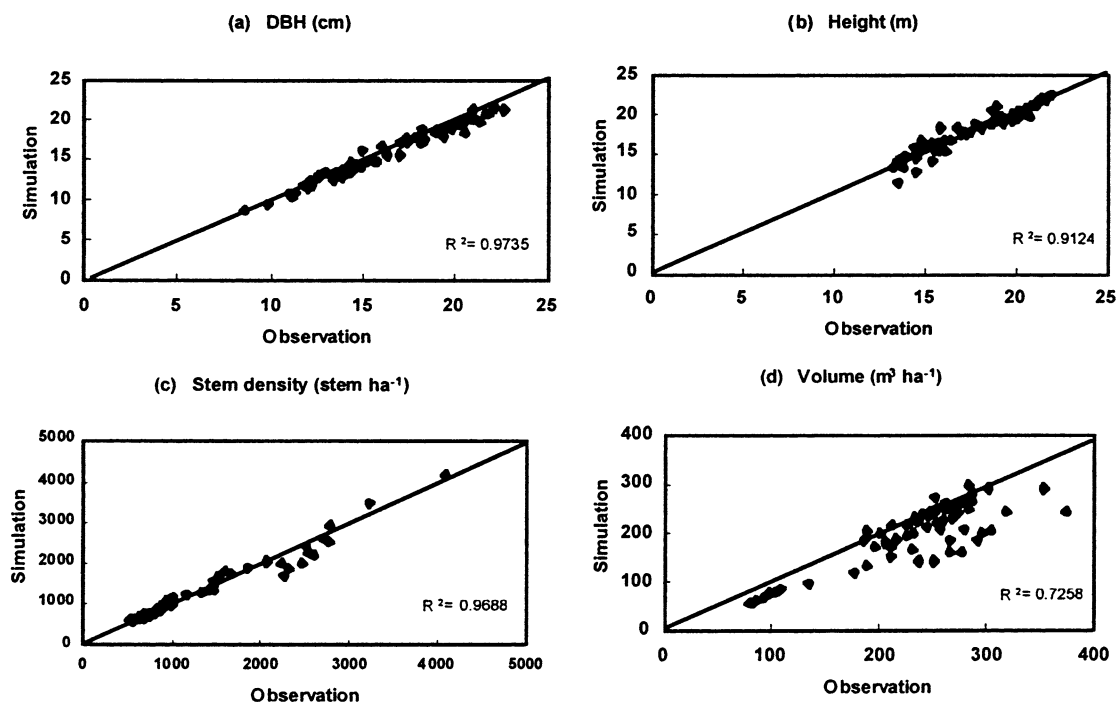

Fig. 2. Comparisons of simulated and observed (a) diameter at breast height (DBH) (cm), (b) tree height (m), (c) stem density (stem ha^{-1}), and (d) tree total volume (m^3 ha^{-1}), respectively (solid diagonal is the 1:1 line).

Table 5
Site information for 12 PSPs in pure jack pine (*Pinus banskiana* Lamb.) stands in northern Ontario

| Plot No.	Longitude, Latitude	Altitude (m)	Year planted	First/last measured year	First/last measured tree density (tree ha^{-1})	First/last measured tree DBH (cm)	First/last measured tree height (m)	First/last estimated tree volume (m^3 ha^{-1})	Soil fertility
PSP001	86°12′W, 49°49′N	290	1848	1952/1987	828/643	18.2/22.6	19.8/21.4	230/271	Moderate
PSP002	86°12′W, 49°49′N	290	1848	1952/1987	1051/841	16.5/20.5	18.8/20.5	230/280	Moderate
PSP003	86°12′W, 49°49′N	290	1848	1952/1987	1075/803	15.9/20.1	18.8/20.4	208/254	Low
PSP004	86°13′W, 49°48′N	320	1880	1952/1987	915/754	18.1/22.1	19.5/21.9	227/301	Moderate
PSP022	86°20′W, 49°47′N	351	1864	1955/1987	841/692	16.5/21.3	18.3/20.3	178/257	Moderate
PSP023	86°20′W, 49°47′N	351	1844	1955/1987	717/569	16.9/20.9	18.4/18.9	171/212	Low
PSP030	86°23′W, 49°51′N	335	1862	1956/1987	1595/939	14.2/19.8	17.1/19.9	238/283	Moderate
PSP039	86°04′W, 49°47′N	290	1923	1957/1987	729/581	11.6/16.9	13.1/17.0	74/135	Low
PSP044	86°04′W, 49°47′N	290	1923	1958/1987	1953/1422	12.0/18.1	14.5/18.7	194/353	High
PSP045	86°04′W, 49°47′N	290	1923	1958/1987	4981/2225	7.6/13.8	12.5/17.3	158/295	High
PSP056	87°03′W, 49°55′N	381	1923	1959/1987	3028/2250	10.1/14.3	12.5/15.8	222/374	High
PSP057	87°03′W, 49°55′N	381	1923	1959/1987	3103/1681	10.2/15.6	13.1/16.8	215/318	High
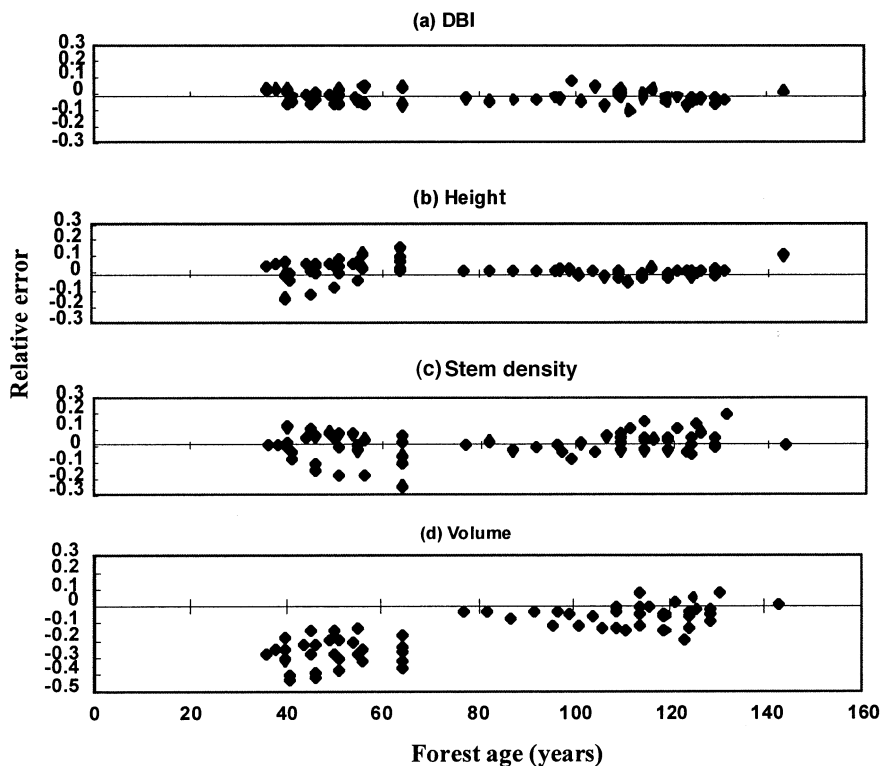
Fig. 3. Simulated relative errors (= [simulation − observation]/observation) over stand age for (a) diameter at breast height (DBH) (cm), (b) tree height (m), (c) stem density (stem ha^{-1}), and (d) tree total volume (m^3 ha^{-1}), respectively.

by TRIPLEX with those observed the PSPs show a good agreement (Figs. 2–4). The mean coefficient of determination (R^2) over the course of five consecutive measuring periods is about 0.97 for DBH (Fig. 2a) and 0.91 for H (Fig. 2b). In general, relative errors of values predicted by TRIPLEX are about ± 10% for DBH and ± 15% for H (Fig. 5). The model provide the best dynamic predictions for trees between 50 and 90 years old.

5.2.2. Stem density and volume

Tree stem density (trees per hectare) measurements indicated that tree mortality occurred during the measured periods (Fig. 6). The results of comparison suggest that simulated average stem density for all 12 PSPs is consistent with the range of independent measurements (Fig. 6a). Overall agreement between simulation and observations is high ($R^2 = 0.97$) (Fig. 2c). However, larger errors

(± 25%) for stands between 30 and 60 years old indicate that the model is less accurate in younger stands (Fig. 5c).

The observations of total tree volume are not available for the study area. Instead they were estimated using measured DBH, and H, and the individual tree total volume equation developed by Honer et al. (1983) (Volume = 0.004331 DBH^2/(0.897 + 106.2319/H)) and summed up for each PSP. This was then compared with volume predicted using TRIPLEX. Results suggest that total volume (m^3 ha^{-1}) from TRPLEX falls within the broad range predicted by Honer's equation. TRIPLEX underestimated tree volume, excepting the PSP004 (Fig. 7c). Overall agreement for total tree volume is poor ($R^2 = 0.73$) (Fig. 2d) with largest relative errors (up to 40%) occurring for stands between ages 30 and 60 (Fig. 5d). This is attributed to the different method of volume calculation i.e. volume estimated using Honer's
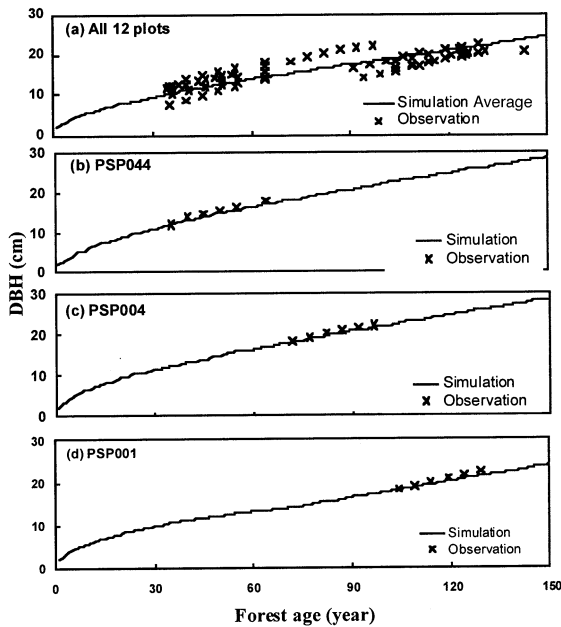
Fig. 4. Comparisons of averaged simulations and observations of diameter at breast height (DBH) (cm) for (a) all 12 PSPs, (b) PSP044, (c) PSP004, and (d) PSP001, respectively.

equation, which may yield local bias when it is used to estimate local stand volume because it was provincial-level equation. Recent studies (Huang et al. 2000; Peng et al., 2001) suggested that the incorrect application of provincial or regional height–diameter models to different ecoregions can produce potential errors for predicting local tree height and volumes. In addition, the cumulative errors generated by height and stem density may have contributed to these discrepancies (Fig. 5b and c). A better test of TRIPLEX would be to compare its predictions with actual volume estimates.

5.2.3. Aboveground biomass

Validation of predicted changes in total stem biomass over several decades is difficult, because data covering the entire simulation period are not available for the PSPs. However, empirical stem biomass models can be used to provide independent estimates of aboveground biomass. Aboveground biomass simulated by TRIPLEX and that estimated by the empirical stem biomass model developed by Hegyi (1972) are compared (Fig. 8).

TRIPLEX did well in predicting aboveground biomass for stands ranging from 70 to 100 years of age (Fig. 8c), but underestimated aboveground biomass for those under 60 or over 100 years (Fig. 8b and d). The reason for this is still unclear. However, average aboveground biomass predicted by TRIPLEX falls within the broad range of empirical estimates over time (Fig. 8a).

5.2.4. Comparison with growth and yield tables

Plonski's normal yield tables, developed for four major northern Ontario tree species in the 1970s (Plonski, 1974), provide a good base for testing the ability of TRIPLEX to predict mean tree diameter at breast height (DBH) and total height (H) for pure jack pine stands in Ontario. Fig. 9 compares simulated average tree diameter (a) and total height (b) over age with those in Plonski's tables. The results suggest that overall agreements for both DBH and H are reasonable. Simulated H averaged over all 12 PSPs is consistent with those of Plonski's Site Class 2 (e.g. median productivity), while predicted DBH is underestimated for stands older than 50 years when compared to the values in Site Class 2 table. This
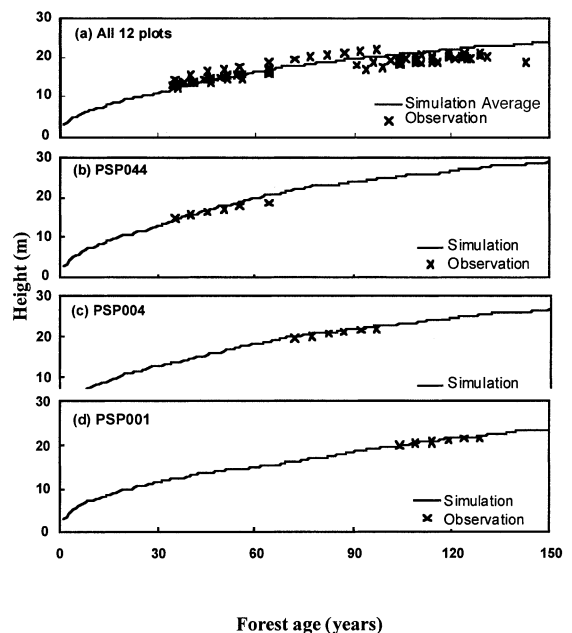

Fig. 5. Comparisons of averaged simulations and observations of tree height (m) for (a) all 12 PSPs, (b) PSP044, (c) PSP004, and (d) PSP001, respectively.
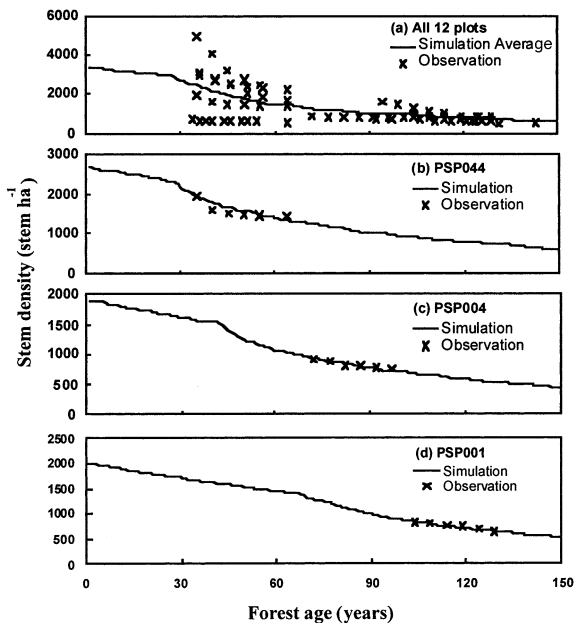
Fig. 6. Comparisons of averaged simulations and observations of stem density (stem ha^{-1}) for (a) all 12 PSPs, (b) PSP044, (c) PSP004, and (d) PSP001, respectively.

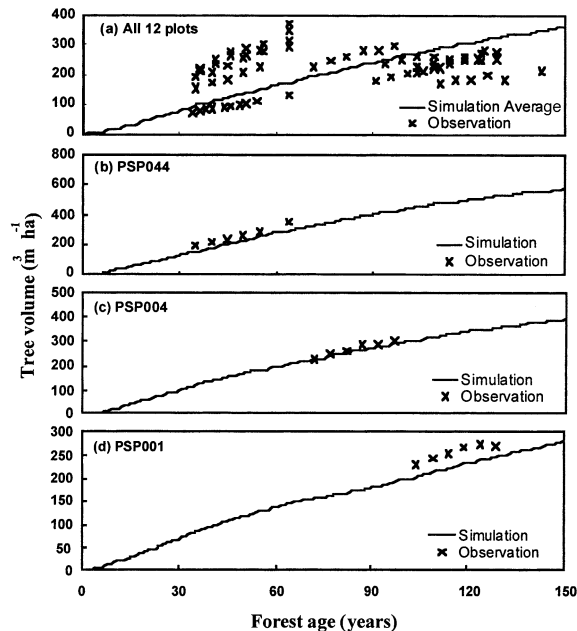Fig. 7. Comparisons of averaged simulations and observations of total volume (m^3 ha^{-1}) for (a) all 12 PSP, (b) PSP044, (c) PSP004, and (d) PSP001, respectively.

may be because Plonski's yield tables are for fully stocked stands but most mature jack pine stands in northern Ontario are less than fully stocked (Plonski, 1974; Woods and Miller, 1998).

6. Sensitivity analysis

Sensitivity analysis is an important step in developing a new model. It provides an opportunity to systematically test model behaviour and gain insight into how the simulated system operates. In this study, a sensitivity analysis was conducted for three selected PSPs by determining the percentage increase in six model outputs considered to be the most important for overall forest growth and C dynamics (Table 6). The sensitivity scenarios involved applying a uniform 10% increase or decrease in mean monthly temperature, monthly precipitation and cloud to previous run scenarios and compare the results.

As expected NPP, total biomass, soil C, DBH, height, and total volume for all plots responded positively to increases in both temperature and precipitation. A 10% increase in mean monthly temperature resulted in increases of 0.1–8.4%, 0.2–10.8%, and 0.1–11.5% in NPP, total biomass, and total volume, respectively. However, the responses of litterfall and soil C to changes in temperature or precipitation were much less pronounced. Tree growth and yield, and C storage responses to decreased cloud were positive for all three PSPs. The largest effect was on NPP, which increased between 1.9 and 8.2%, with a 10% decrease in cloud cover, because the amount of cloud, in TRIPLEX, directly affects PAR which controls canopy photosynthesis. In this study, cloudy sky PAR was assumed to be 20% of that of clear sky (Bossel, 1996). Accurate estimation of key model parameters is critical to achieve the best simulation precision.

7. Discussion

7.1. Problems of applying process-based models in forest management

Process-based C balance models usually share

the same general structure and key processes. They calculate radiation interception, canopy photosynthesis, or GPP, estimate NPP, and then allocate the resultant carbon to different components of trees. They all use a similar modifier scheme to account for the effects of temperature, moisture, and nutrition. Unfortunately, forest managers rarely use process-based forest growth models as a tool for forest management decision making (Landsberg and Gower, 1997; Battaglia and Sands (1998), Mäkelä et al., 2000) for a variety of reasons:

- Many current process-based models, such as FOEST-BGC (Running and Coughlan, 1988), TEM (Melillo et al., 1993), CENTURY (Parton et al., 1987, 1993), PnET (Aber and Federer, 1992), TREGROW (Weinstein et al., 1991), and Hybrid v3.0 (Friend et al., 1997), are not appropriate for management applications because they are not designed to predict stand characteristic such as basal area, mean

tree diameter, height, and annual mortality, and thus the outputs are not directly useful in management planning (Landsberg and Waring, 1997);
- Most process-based models are too complex and require a large amount of information (the number of parameter and input variables) beyond what is readily available to forest managers, making them of minimal interest to practicing foresters and forest managers (Sands, 1988; Landsberg and Coops, 1999);
- Most models lack a user-friendly modeling interface and their documentation is insufficient, making them difficult for forest managers to use (Peng, 2000b).

Forest managers are increasingly interested in using C balance process-based approaches for assessing the sustainability of forest ecosystem productivity under short-rotation forestry and the potential effects of projected global warming and increasing atmospheric CO_2 concentration. There has been growing interest in developing process-based C balance models with which forest growth and yield can be simulated (Bossel, 1996; Landsberg and Waring, 1997; Mäkelä et al., 2000). In this study, we developed a new model, TRIPLEX, which includes both empirical and mechanistic. For example, we have incorporated climate variables (e.g. temperature, precipitation, and radiation) to enhance the ability of empirical growth and yield models to predict the effects of climate change on forest productivity. To improve the ability of process-based models to address forest management issues, we have added a forest growth and yield submodel that is able to provide outputs such as tree height, diameter, mortality and volume that are useful in forest management decision making. We believe that the hybrid approach used in TRIPLEX is useful for bridging the gap between empirical forest growth and yield and process-based C balance models.

7.2. Potential to link model with remote sensing and GIS

A grand challenge in applying forest simulation models at landscape or regional levels is the issue
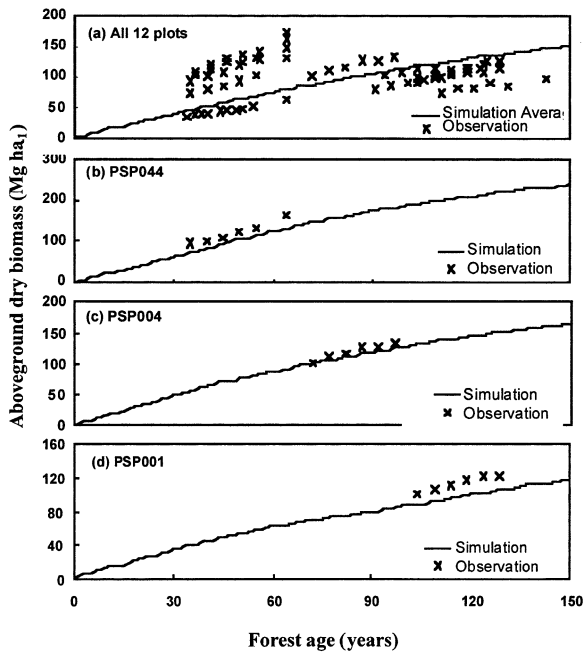

Fig. 8. Simulation of aboveground biomass with different stand ages compared to estimates of the empirical biomass equation of Hegyi (1972) (aboveground biomass = 0.0919 DBH 2.4206), which was developed by fitting observations from 77 jack pine PSPs in northern Ontario.
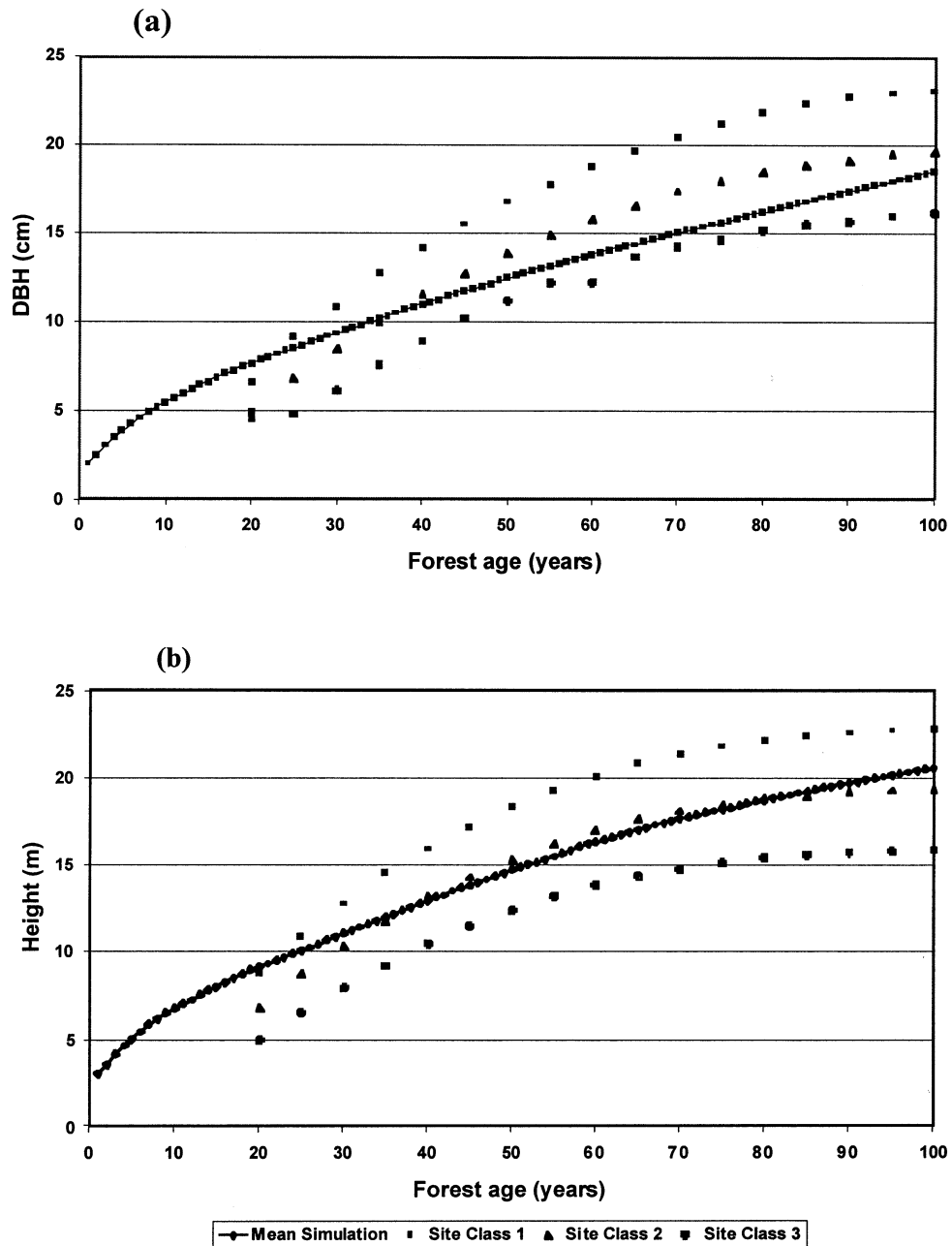
(a)

(b)

Fig. 9. Comparisons of simulation averaged over all 12 PSPs and estimations of Plonski's normal yield table (Plonski, 1974) for jack pine stands for (a) diameter at breast height (DBH) (cm) and (b) total tree height (m). Site Class 1, 2 and 3 represent high, medium, and low site productivity, respectively.

of scaling (Wu, 1999). The inherent spatial heterogeneity in biotic and abiotic variables makes it difficult to meaningfully use a small number of

site-level field studies to evaluate large-scale responses of forest ecosystems to natural and human perturbations over time. GIS is a powerful

tool for integrating spatially referenced databases as multiple layers of driving variables. These linked multiple layers can be used to model the responses of ecosystems to different perturbations. However, GIS still cannot effectively deal with temporal scale, nor can it explain the spatial patterns of ecosystem structure and function. The obvious solution to this limitation is to link GIS with stand-level models like TRIPLEX.

One of our primary goals in developing the TRIPLEX model was to scale up from the stand to the regional level. TRIPLEX, similar to 3-PG (Landsberg and Waring, 1997), has the potential to use remote sensing data as input to estimate canopy photosynthetic capacity (PAR) and LAI through satellite-derived normalized difference vegetation index within a cell for a given month. GIS can help address data integration problems associated with using multiscale data from a com-

bination of ground-based growth and yield plot measurements and remote sensing images. Recently, Coops et al. (1998) and Coops (1999) have successfully used a modified version of 3-PG to predict forest productivity across landscapes using NOAA–AVHRR and Landsat MSS imagery. We believe that combining GIS and remote sensing with TRIPLEX in future can improve its ability to predict forest growth and C dynamics at large scales, and allow it to be coupled with a carbon budget model (e.g. CBM-CFS2, Kurz and Apps, 1999) to predict future forest C budgets at provincial or national scales (Peng et al., 2000).

7.3. Model validation and future improvements

A major challenge with all process-based models is validation. Most process-based C balance models rarely use conventional forest growth and

Table 6
Predicted sensitivity of key variables to changes in climatic variables for three selected jack pine PSPs used in this study (values are percent change)

Jack pine stands	Temperature		Precipitation		Cloud	
	+10%	−10%	+10%	−10%	+10%	−10%
PSP044						
NPP	+0.1	−4.3	+3.1	−4.9	−3.0	+1.9
Total biomass	+0.2	−5.2	+4.0	−5.9	−3.1	+3.1
Litterfall	−1.0	−2.3	−0.1	−0.1	−2.9	+2.8
Soil carbon	0	0	−0.2	+0.1	−0.1	+0.1
DBH	+0.1	−2.4	+1.6	−2.5	−1.2	+1.2
Height	+0.1	−2.5	+1.8	−2.7	−1.4	+1.4
Total volume	+0.1	−5.6	+4.3	−6.4	−3.3	+3.2
PSP004						
NPP	+4.6	−6.7	+2.6	−3.8	−3.4	+2.5
Total biomass	+4.0	−7.9	+2.9	−4.1	−3.9	+4.2
Litterfall	+1.2	−3.7	+0.5	−0.7	−3.1	+3.1
Soil carbon	+0.1	−0.4	+1.5	−2.5	−0.4	+0.4
DBH	+1.4	−3.5	+1.5	−2.3	−1.8	+1.8
Height	+1.5	−3.6	+1.5	−2.3	−1.8	+4.4
Total volume	+4.2	−8.6	+3.1	−4.4	−4.2	+3.1
PSP001						
NPP	+8.4	−8.8	+2.7	−3.8	−4.0	+8.2
Total biomass	+10.8	−11.8	+3.2	−4.7	−4.9	+4.8
Litterfall	+3.0	−1.8	+1.1	−1.0	−1.7	+2.0
Soil carbon	+1.7	−2.0	+0.5	−0.7	−1.0	+2.0
DBH	+5.2	−7.1	+1.7	−2.7	−2.8	+2.5
Height	+5.5	−7.0	+1.7	−2.6	−2.9	+2.5
Total volume	+11.5	−12.7	+3.4	−5.0	−5.2	+5.0

yield plot measurements to test model prediction accuracy over decades (Landsberg and Waring, 1997; Landsberg and Coops, 1999). The results presented in this study demonstrate that TRIPLEX is able to provide reasonable estimates of DBH, *H*, and stem density for jack pine stands in northern Ontario. Simulated key variables (e.g. total volume and aboveground biomass) are in good agreement with empirical estimates. Model sensitivity analyses indicate that a wide range of responses to identical changes in climatic drivers can be expected. However, our model validation is still partial, mainly due to the absence of observed data on these selected plots. More rigorous testing of the model's ability to simulate NPP, belowground biomass, and soil C, N and water dynamics for various forest ecosystems is a high priority in the ongoing development of the model. Moreover, additional modules of the effects of CO_2 fertilization and ecosystem disturbances (e.g. fire, harvesting, insect and disease) on forest growth and C dynamics need to be included in future versions of TREPLEX.

Acknowledgements

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