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Assessing the generality and accuracy of the TRIPLEX model using in situ data of boreal forests in central Canada

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Abstract

TRIPLEX1.0 is a hybrid model that integrates three well-established process models including 3-PG, TREEDYN3.0 and CENTURY4.0. We have conducted calibrations using eight sites to determine and generalize parameters of the TRIPLEX. We also performed model validation using 66 independent data sets to examine the model accuracy and the generality of its application. Simulations were conducted for plots with large sample size from the boreal ecosystem atmosphere study (BOREAS) program, including the northern study area (NSA) near Thompson, Manitoba (55.7° N, 97.8° W) and the southern study area (SSA) near Prince Albert, Saskatchewan (53.7° N, 105.1° W). The calibrations and simulations emphasized on generating average parameters and initial statuses for applying a complex model in a broad region where site detailed information such as photosynthetic capacity, soil carbon, nutrient, soil water, and tree growth is not always available. A suggestion was presented regarding adjusting the sensitive parameter by estimating tree growth rate corresponding to different site conditions. The study actually presented a reasonable and balanced parameter generalization procedure that did not lead to a significant reduction of model accuracy, but did increase the model practicability. The comparison of observations and simulations produced a good agreement for tree density, mean tree height, DBH, soil carbon, above-ground and total biomass, net primary productivity (above-ground) and soil nitrogen in both short- and long-term simulation. Results presented here imply that the set of parameters generalized and suggested in this study can be used as basic referenced values, in which TRIPLEX can be applied to simulate the general site conditions of boreal forest ecosystems.

Keywords: Ecosystem model; Simulation; Boreal forest; Carbon balance; Model validation

1. Introduction

The importance of boreal forests, which represent approximately 11% of the earth's total land area (Bonan and Shugaet, 1989), has been recognized in the global carbon cycle. Modeling the ecosystem behavior and dynamics of boreal forests is a powerful approach used by many ecology scientists. In forest ecosystems research, a number of simulation models have been developed over the last decade. These models predict the seasonal and interannual patterns of carbon and water vapor exchange at varying spatial and temporal resolutions (Coops et al., 2001). Previous simulation models of forest ecosystem mainly included two types: empirical and process-based (Kimmins, 1988; Dixon et al., 1990; Ågren et al., 1991; Kimmins et al., 1995). Subsequently, hybrid simulation models have been used extensively for studying ecosystem structure and functions since the 1990's (Levin et al., 1993; Friend et al., 1997; Battaglia et al., 1999; Kimmins et al., 1999; Peng et al., 2002). Empirical or mechanistic process-based models have their advantages and disadvantages. Hybrid modeling is a promising approach that bridges the gaps between empirical and process-based models (Mäkelä et al., 2000; Peng, 2000a,b; Johnsen et al., 2001). Recently, TRIPLEX, a new hybrid model that integrated empirical models and process-based models, was developed for predicting forest growth, carbon and nitrogen dynamics (Peng et al., 2002). The TRIPLEX combines photosyn-

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thetically active radiation (PAR) submodel of TREEDYN3.0 (Bossel, 1996), forest production submodel of 3-PG (Landsberg and Waring, 1997), tree growth and yield submodel of TREEDYN3.0 (Bossel, 1996), and soil carbon and decomposition submodel of CENTURY4.0 (Parton et al., 1993). TRIPLEX simulates key dynamic processes of forest ecosystems, including gross primary productivity (GPP), forest growth, soil water balance, and carbon and nitrogen distribution. The significance exhibited by TRIPLEX provides a notion and approach for using existing models effectively to resolve problems facing us.

To test model applicability, models should be evaluated in order to build confidence in their validity (Rauscher et al., 2000). The primary importance of validation is to test whether the model output conforms with its stated purpose (Rykiel, 1996; Rauscher et al., 2000). To date, the calibration and testing of TRIPLEX was conducted only for limited stand variables (such as tree height and diameter, tree density and above-ground biomass) for jack pine (*Pinus banskiana*) stands in northern Ontario in Canada (Peng et al., 2002). To test the accuracy and practicability of the TRIPLEX in a broad region, this study continued the calibration beyond the work by Peng et al. (2002) as mentioned above. Due to the lack of a comprehensive data set, model calibration and validation are always a challenge. TRIPLEX was facing two problems: some parameters were defined differently for different models, and some field data used to set parameters were not available for a broad region covering various sites. There are many studies related to the discussion of model parameterization for the boreal forests. Normal processing is established to determine or select mean values from the literature, and to provide some ranges of parameter values for specified tree species (Wullschleger, 1993; Kimball et al., 1997, 2000; Kolström, 1998; Peng et al., 1998; Price et al., 1999; Coops et al., 2001; Wang et al., 2001). However, due to the complexity of TRIPLEX integrating three empirical and process-based models, TRIPLEX can neither acquire sufficient reference parameters from literature, nor accept ranges of parameters rather than a fixed parameter since frequently selecting parameters in broad ranges for various site conditions will lead to a number of parameter values in a model. This would dissatisfy the original desire to minimize the number of input parameters in developing the TRIPLEX (Peng et al., 2002).

This paper reported a comprehensive process of model evaluation including model calibration, parameter determination and generalization, and model validation. Parameters were simplified and determined by generating average parameters for wide regions. The objectives of this study were: (1) to carry on a validation of the hybrid model in a wide area of boreal forest, and (2) to estimate the accuracy and practicability of the TRIPLEX for boreal forests in central Canada.

2. Data and methods

2.1. Study procedure and strategy

The studying procedure includes three steps: (1) Selecting some sites in the boreal ecosystem atmosphere study (BOREAS) region and conducting calibration of the TRIPLEX using the data collected from these selected sites, in which ecological conditions and initial data required by the TRIPLEX should be detailed and representative of the BOREAS region, although the number of samples can be less. This step determines parameters that make accuracy of the TRIPLEX as high as possible. (2) Performing a parameter generalization following the results of the first step, i.e., parameters are calibrated first for some representational sites, and generalized then for a wide region. Some sensitive parameters can be adjusted by estimating the growth rate corresponding to different site conditions (details are explained in Section 3 of this paper). This makes TRIPLEX to be general and allows the model to be used in the boreal forest region in central Canada. (3) Conducting model validation for independent plots with large sample size in a more extensive area for testing the accuracy and generality of the TRIPLEX. This procedure is based on a consideration that emphasizes average parameters and initial states for applying a complex model in a broad region, in which site details are not always available for some conditions such as PAR, soil nutrient, soil water, and so forth.

2.2. Study area

The study region, located in central Canada (Fig. 1), consists of the northern study area (NSA) near Thompson, Manitoba (55.7° N, 97.8° W) and the southern study area (SSA) near Prince Albert, Saskatchewan (53.2° N, 105.7° W) established by the boreal ecosystem-atmosphere study (Sellers et al., 1997). Eight sites (Table 1) are selected for TRIPLEX calibration, and 66 independent sites (Table 2) are compiled and used for the model validation. The mean monthly air temperature in NSA and SSA ranges from −25 °C to 15.7 °C and from −19.8 °C to 17.6 °C, respectively. Annual average precipitation is about 390 mm at Prince Albert and 542 mm at Thompson. Permafrost did not occur in the top 2 m of soil in any of the selected stands. Most soil types are sand or sandy clay loam in aspen and jack pine stands, while the soil type in spruce stands is dominated by clay.

2.3. Data

2.3.1. Forest stand data for model calibration

Data for the calibration of TRIPLEX are presented in Table 1. Eight sites measured by Gower et al. (1997) in NSA and SSA were selected as samples for model

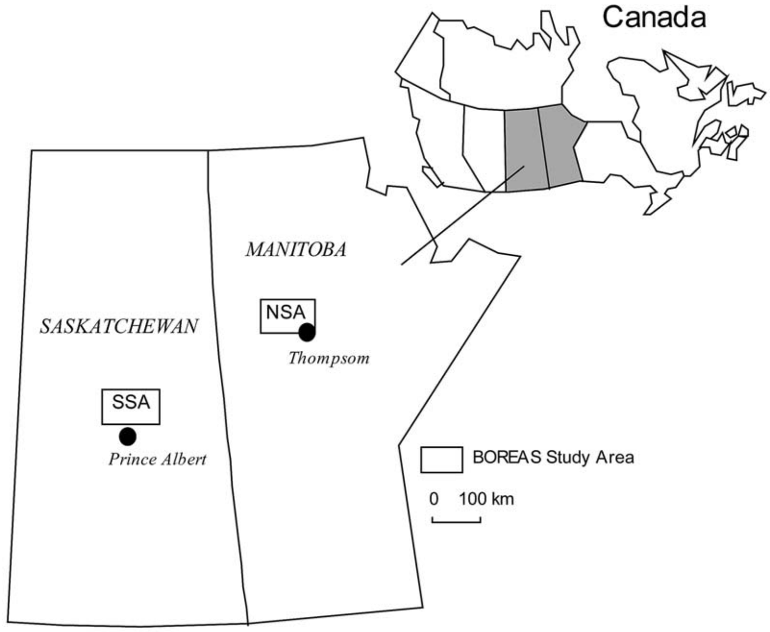

Fig. 1. The boreal case study region, located in central Canada, that consists of the northern study area (NSA) near Thompson, Manitoba (55.7° N, 97.8° W) and the southern study area (SSA) near Prince Albert, Saskatchewan (53.2° N, 105.7° W).

Table 1
Observations of Gower et al. (1997) were used to calibrate parameters of the TRIPLEX for trembling aspen, black spruce and jack pine at northern study area (NSA) and southern study area (SSA) of BOREAS

	Forest type	Age (years)	Trees (ha^{-1})	Mean tree height (m)	DBH (cm)	Above-ground biomass ($t\ C\ ha^{-1}$)	Soil carbon ($t\ C\ ha^{-1}$)
NSA	NOA[a]	53	1960	13.8	12.5	56.3	97.2
	NBS[b]	155	5450	9.1	8.5	56.2	418.4
	NYJP[c]	15	15,160	2.9	2.1	7.5	28.4
	NOJP[d]	63	1280	10.3	11.1	23.3	25.8
SSA	SOA[e]	67	980	20.1	20.5	92.6	36.0
	SBS[f]	115	5900	7.2	7.1	48.1	390.4
	SYJP[g]	25	10,670	3.7	3.2	12.3	20.2
	SOJP[h]	65	1190	12.7	12.19	30.9	14.2

[a] NOA: northern old aspen.
[b] NBS: northern black spruce.
[c] NYJP: northern young jack pine.
[d] NOJP: northern old jack pine.
[e] SOA: southern old aspen.
[f] SBS: southern black spruce.
[g] SYJP: southern young jack pine.
[h] SOJP: southern old jack pine.

calibration in terms of above-ground biomass, soil carbon, tree height and diameter at breast height (DBH). These sites involve major boreal tree species including trembling aspen (*Populus tremuloides*), black spruce (*Picea mariana*), and jack pine (*Pinus banskiana*). The four forest types used for TRIPLEX calibrations are old aspen (OA), old black spruce (OBS), young jack pine (YJP) and old jack pine (OJP). All these trees are overstory and dominant at their respective study sites. Understory vegetation was not considered in this study. The data for above-ground biomass and net primary production (NPP) were collected by Gower et al. (1997). They estimated above-ground biomass of tree components using allometric equations, and calculated above-ground net primary production (ANPP) as the sum of annual biomass increment, in which overstory biomass increment was measured in variable radius plots using a 10 basal area factor prism or established inside each of the four fixed area replicate plots.

Table 2
Observations used to validate the TRIPLEX. The ranges of measured variables from 66 independent sites located in northern study area (NSA) and southern study area (SSA) in 1994 (Newcomer et al., 2000b)

	Forest type	DBH (cm)	Mean basal area (m^2)	Above-ground biomass (t C ha^{-1})
NSA	NOA[a]	1.5–18.9	0.7–74.1	0.3–70.2
	NBS[b]	1.2–19.2	0.5–59.8	0.2–92.2
	NJP[c]	0.7–18.5	1.0–33.9	1.0–60.0
SSA	SOA[d]	3.6–25.0	1.2–50.6	1.9–124.9
	SBS[e]	2.0–14.2	1.0–76.7	0.7–87.2
	SJP[f]	1.7–17.7	1.2–46.0	0.4–63.7

[a] NOA: northern old aspen.
[b] NBS: northern black spruce.
[c] NJP: northern jack pine.
[d] SOA: southern old aspen.
[e] SBS: southern black spruce.
[f] SJP: southern jack pine.

2.3.2. Forest stand data for model validation

Table 2 shows key variables in which data are available for a wider range of site conditions that were described by 277 plots measured from 66 independent sites located in NSA and SSA. All the field data were obtained from Newcomer et al. (2000a,b). Six forest types including young aspen (YA), old aspen, young black spruce (YBS), old black spruce, young jack pine, and old jack pine were used for TRIPLEX simulation. Simulation results were compared with the observations of 66 independent sites compiled by the BOREAS region (Newcomer et al., 2000a,b).

2.3.3. Climate data

Monthly patterns of temperature and precipitation (Fig. 2), which generalized averages of climate conditions in both NSA and SSA, were used for TRIPLEX simulations. Precipitation and temperature data were obtained from Atmospheric Environment Service (AES, 1983), and the vapor pressure deficiency (VPD) was derived from monthly average precipitation and temperature as follows.

$$svp = 6.1076*\exp((17.269*T)/(T + 237.3)) \quad (1)$$

$$vp = RH*svp/100 \quad (2)$$

$$\mathrm{VPD} = svp - vp \quad (3)$$

where svp is saturation vapor pressure (mbar), vp is vapor pressure (mbar), T is average temperature for the month (°C), and RH is relative humidity (%) that was collected from Newcomer et al. (2000c).

The ratio of frost days required for calculating GPP was determined by the average monthly temperature. A 100% ratio of frost days means a minus average tem-

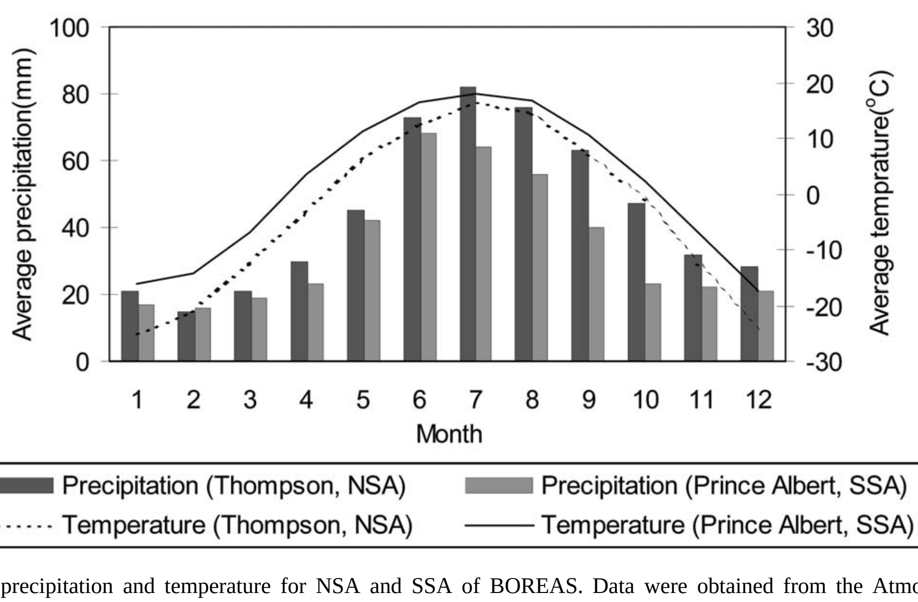

Fig. 2. Mean monthly precipitation and temperature for NSA and SSA of BOREAS. Data were obtained from the Atmospheric Environment Service (AES, 1983).

perature in a month, and a 50% ratio of frost days in a month means that the average temperature of the month is from 0 °C to 5 °C.

2.4. Model description and parameterization

2.4.1. TRIPLEX

TRIPLEX is a generic hybrid simulation model, and was constructed using an objective oriented programming language C++. The structure of the TRIPLEX includes four parts: (1) forest production submodel that estimates PAR, GPP, and above-ground and below-ground biomass; (2) soil carbon and nitrogen submodel that simulates carbon and nitrogen dynamics in litter and soil pools; (3) forest growth and yield submodel that calculates tree growth and yield variables (e.g., height, diameter, basal area, and volume); (4) simple soil water balance submodel that simulates water balance and dynamics. The simulation of the TRIPLEX involves key processes and dynamics including PAR, GPP, forest growth, biomass, soil carbon, soil nitrogen, and soil water. All the simulations in this case study were conducted with a monthly time step, while the output of simulations is summed up yearly.

The input of TRIPLEX is simple and mainly includes the location (latitude), climate, and some initial site conditions. In TRIPLEX, the PAR was calculated as a function of solar constant, radiation fraction, solar height, and atmospheric absorption; GPP was calculated as a function of received PAR modified by conversion constant, leaf area index (LAI), forest age, mean monthly air temperature, soil drought, and percentage of frost days within a month; NPP was estimated with a fixed fraction (0.39) of GPP for boreal forest ecosystem as suggested by Ryan et al. (1997); empirical coefficients in 3-PG (Landsberg and Waring, 1997) were utilized for calculating carbon allocation; forest growth was calculated from annual increments of individual tree height and diameter (Bossel, 1996); soil water, carbon and nitrogen were calculated by the corresponding modules in CENTURY4.0 model (Parton et al., 1993). The detailed description of the TRIPLEX feature, structure, mathematical representation, sensitivity analysis and building strategy were previously provided by Peng et al. (2002) and Liu et al. (2002).

2.4.2. Model initialization

For simulating forest ecosystem processes and dynamics, TRIPLEX requires some initial values that consist of stand variables describing conditions of forest stands and soils. There are three key variables related to initial conditions for forest growth and yield simulation. They are tree density (number of trees), tree height, and diameter at breast height. Other initial conditions for describing soil status include carbon level and soil water. These initial data were available from the BOREAS field measurements which had been collected from 1993 to 1996 and published by the BOREAS Information System, NASA Goddard Space Flight Center (Newcomer, et al., 2000a,b,d). In case soil nutrition and soil water were not available for specific sites, the average values over the entire region or similar ecological conditions can be utilized, e.g. the database (Siltanen et al., 1997) describing soil conditions in a wider region.

2.4.3. Model parameters

TRIPLEX was designed minimizing the number of input parameters required for its practical use, and was parameterized to present tree boreal species (aspen, black spruce and jack pine) in this study. A list of parameters used to calibrate the TRIPLEX is presented in Table 3. Basically, there are three types of parameters listed in Table 3: (1) unknown parameters that need to be adjusted and determined with calibration, (2) knowable parameters that can be estimated from site data, and (3) known parameters that were derived from published references or assumptions. The main goal of the model calibration was to obtain these unknown parameters for TRIPLEX simulation.

As shown in Part 1 of Table 3, the ranges of two variables, MiuNorm (normal mortality ratio) and MiuCrowd (crowding mortality ratio), were estimated from the literature, in which the normal mortality ranges from 0.002 to 0.01 when the tree density is less than 6000 trees ha^{-1} (Plonski, 1974; Bossel, 1996). The crowding mortality ratio was determined to be 0.02 (Bossel, 1996).

The reasons for determining some parameters listed in Part 3 of Table 3 are explained as follows. The initial tree age was set to zero supposing that there are no tree height and diameter growth. Maximum tree age was set up as 200 years, which means the TRIPLEX will no longer calculate the growth of a stand over that age. Depending on the measurement of soil texture from 277 plots of NSA and SSA (Newcomer et al., 2000a), the averaged percentages of sand, clay, and silt are 70% (greater than 50% in 70% of the plots), 10% (less than 13% in 70% of the plots), and 20% (less than 23% in 70% of the plots), respectively. We used averaged percentages of sand, clay, and silt for the TRIPLEX calibration and validation. A 50% relative soil water content was given for an averaged water level, supposing that 100% means flooding. The stem loss ratio was supposed to be zero for simplifying the calculation. Other assumptions are that 20% nitrogen in the soil was available for tree growth, 50% fraction of water flowed to stream, 50% fraction of water penetrated to deeper layers as flowed to deep storage (disregarding the amount of trees used and evaporation), and 30% fraction of deep storage water flowed to stream.

Fig. 3 shows the relationship of tree density and DBH, and a regression curve (Curve a) created by the least squares method. Assuming that (1) this curve represents

Table 3
Parameters used for the calibration of TRIPLEX

Parameter	Description	Values/note
Parameters to be determined by calibration		
Folpra	Coefficient for NPP allocation	Depends on calibration
Folprn	Coefficient for NPP allocation	Depends on calibration
Stempra	Coefficient for NPP allocation	Depends on calibration
Stemprn	Coefficient for NPP allocation	Depends on calibration
GamaR	Root loss ratio	Depends on calibration
MaxGama	Max foliage loss ratio	Depends on calibration
Parameters determined by site data		
Lat	Latitude	Depends on site
Tavg	Average monthly temperature	Depends on site
CSP	Wood C density (t C m^{-3})	Depends on site
Parameters from the literature or assumed:		
Age = 0	Initial of tree age	Assumption
AgeMax = 200	Maximum tree age	Assumption
Tveg = 5	Temperature of vegetation begin and end	a
TaMin	Min temperature for producing GPP	a
TaMax	Max temperature for producing GPP	a
HdMin	Min height–diameter	a
HdMax = 80	Max height–diameter	a
Sla = 6	Specific leaf area	b
Topt = 15	Optimum temperature for producing GPP	b
Ts = 0.7	Sand content rate	f
Tc = 0.1	Clay content rate	f
T = 0.2	Silt plus clay content	f
Ccpp = 0.39	Convert GPP to NPP	c
MoistRatio = 0.5	Relative soil water content	Set as 50%. 100% means flood
NitrogenFactor = 0.2	Nitrogen factor	Set as 20% for growth
Cloud = 0.4	Cloud ratio for a month	a
AvailableWater = 250.0	Maximum soil water (mm)	e
AlphaC = 0.05	Canopy quantum efficiency	d
GamaS = 0	Stem loss ratio	Assumption
CGama = 15	Parameter for foliage loss ratio	d
KGama = 0.12	Parameter for foliage loss ratio	d
Lnr = 0.26	Lignin-nitrogen ratio from *N* Module	e
K1 - K8	Max decomposition rate	e
A1 = 15	Soil water depth of layer 1 (cm)	e
A2 = 15	Soil water depth of layer 2 (cm)	e
A3 = 15	Soil water depth of layer 3 (cm)	e
AWL1 = 0.5	Relative root density (layer 1) (cm)	e
AWL2 = 0.3	Relative root density (layer 2) (cm)	e
AWL3 = 0.2	Relative root density (layer 3) (cm)	e
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 = 15	Crown to stem diameter ratio	a
MiuNorm	Normal mortality ratio	g
MiuCrowd	Crowding mortality ratio	a

a: Bossel, 1996; b: Kimball et al., 1997; c: Ryan et al., 1997; d: Landsberg and Waring, 1997; e: The values are given by CENTURY (Parton et al., 1993); f: Field data (Newcomer et al., 2000a); gPlonski, 1974 and Bossel, 1996.

approximately the average of DBH at each tree density, and (2) there is an area that ranges greater and lesser than the value of Curve a plus 30% (see Curve c in Fig. 3) and minus 30% (see Curve b in Fig. 3), the point representing a stand in Fig. 3 should be usually higher above Curve c or lower below Curve b. Stands above Curve a plus 30% achieve crown closure approximately, and minus 30% does the opposite depending on our estimation using the density management diagram (Archibald and Bowling, 1995). In the viewpoint of the density management diagram, Curves a, b and c can be viewed as the curves that suppose the extent of tree height. Actually, the tree height reflects the growth rate of a tree more directly except in over-mature forests, and estimating the growth rate is better via analyzing the relationship of tree density and height than DBH, if tree

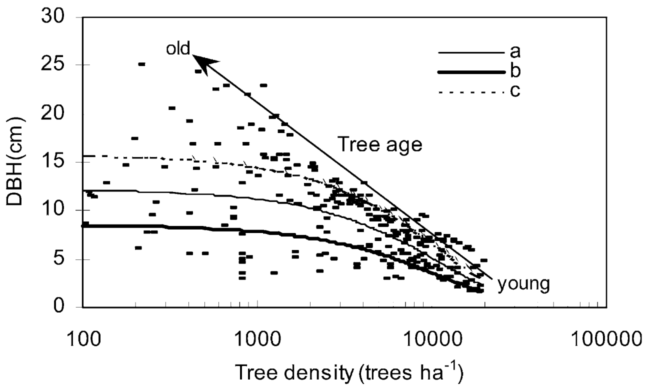

Fig. 3. The relationship between tree density (trees ha^{-1}) and DBH (cm). This relationship was used for determining the parameter of Stemprn, which affects the biomass allocation to stem and foliage. The curve "a" illustrates a regression function (DBH = 12.198 exp(−0.000087 tree density)) that represents averaged site condition, for which the value of Stemprn is intermedium. The "b" and "c" represent lower and upper limit, respectively, for which the value of Stemprn can be adjusted accordingly. Data were collected from 66 BOREAS sites (n = 277) (Newcomer, et al., 2000 a,b).

height data are available. In the area between Curve b and c of Fig. 3, generalized parameter Stemprn in parentheses in Table 4 was used for those plots with normal growth rate. Based on this, the parameter Stemprn was adjusted as in the following rule for abnormal growth rates:

$$\text{Stemprn} = \begin{cases} 3.3 \text{ (DBH > the value of Curve c)} \\ \text{value of generalized parameters (the value of Curve c < DBH < the value of Curve b)} \\ 2.6 \text{ (DBH < the value of Curve b)} \end{cases} \quad (4)$$

Curves a, b and c:

$$\text{DBH} = D\exp(-0.000087 \text{ Tree density}) \quad (5)$$

where D = 12.198, 8.539 and 15.857 for Curves a, b and c, respectively.

In Table 4, some parameters, such as the latitude (*Lat*), and average temperature (*T*avg) were directly determined by site. The wood C density (t C m^{-3}) was calculated from the collected data of the boreal ecosystem-atmosphere study (Newcomer et al., 2000d).

3. Results and discussions

3.1. Model calibration

The purpose of the calibration was to determine parameters that are important for the application of TRIPLEX to the areas of NSA and SSA. Table 4 shows parameters that were adjusted closely in the calibration based on the data shown in Table 1. Fig. 4 illustrates excellent correlation coefficients (r^2) between observations and simulations that range from 0.93 for DBH and total biomass to 0.99 for tree density. The calibrations were highly correlated with field measurement for tree density, height, DBH, soil carbon, above-ground biomass. All r^2 coefficients are above 0.90. The calculation errors of calibration were less than 10%, suggesting that the TRIPLEX calibration for those variables is reliable. However, in Fig. 4D, r^2 is very high for soil carbon due to the lack of full range of observations. There are two sets of extreme values, which make the tendency more observable and the correlation coefficient higher. Better calibrations using larger sample size may be helpful and necessary for large scale applications of the TRIPLEX.

To make the TRIPLEX applicable to the NSA and SSA of BOREAS, parameters determined by the model calibration were generalized as averaged values, presented in parentheses in Table 4. These generalized parameters simply represent some sites with similar stand conditions. Fox example, we used averaged temperature (*T*avg) for the same area (NSA or SSA), and averaged growth coefficient (Stemprn) for the same tree species in the same area.

3.2. Parameter generalization and its effects on model accuracy

To examine the magnitude errors caused by parameter generalization (averaging), a simulation using generalized parameters was performed for eight selected sites as shown in Table 1. The calibration using the generalized parameters was also highly correlated with field measurements, but the lower range of the correlation coefficients was slightly smaller than that of the calibration using the non-generalized site specific parameters (Fig. 4). The r^2 ranges from 0.93 (see point a in F of Fig. 4) to 0.99 (see point a in D of Fig. 4) by using original parameters listed in Table 4 and from 0.78 (see point b in F of Fig. 4) to 0.99 (see point b in D of Fig. 4) by using the generalized parameters listed in parentheses in Table 4. This difference was mainly due to the limitation of available field data. We usually expect more field data for the model calibration with higher accuracy; however, field sites meeting all calibration requirements of TRIPLEX were not many in both NSA and SSA. To improve the precision of the model, calibration represents a challenge in future research. The more data we use, the better model calibration we can achieve, although the differences in r^2 may vary.

The model accuracy is an important issue as regards the practical application of the model. However, there always exists the dilemma of choosing a set of suitable parameters for balancing the accuracy and generality of the model. As discussed previously, the generality of the model was expected to apply TRIPLEX for a typical boreal forest ecosystem in central Canada. For this purpose, a smaller calculation error and higher r-squared value are generally required. Depending on the compari-

Table 4
Parameters used for individual sites for the calibration of the TRIPLEX. The calibration data is shown in Table 1.

Parameter	NOA[a]	NBS[a]	NYJP[a]	NOJP[a]	SOA[a]	SBS[a]	SYJP[a]	SOJP[a]
Parameters determined with calibration								
Folpra	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}
(Average)	(Same as above)							
Folprn	2.235	2.235	2.235	2.235	2.235	2.235	2.235	2.235
(Average)	(Same as above)							
Stempra	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}
(Average)	(Same as above)							
Stemprn	3.3	2.95	3.3	3.1	3.32	2.95	3.2	3.2
(Average on same species)	(3.3)	(3.0)	(3.2)	(3.2)	(3.3)	(3.0)	(3.2)	(3.2)
GamaR (SD = 0.0012)[b]	0.006	0.008	0.005	0.005	0.004	0.005	0.005	0.005
(Average)	(0.0054)	(0.0054)	(0.0054)	(0.0054)	(0.0054)	(0.0054)	(0.0054)	(0.0054)
MaxGama (SD = 0.0007)	0.01	0.01	0.01	0.01	0.008	0.01	0.01	0.01
(Average)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
MiuNorm (SD = 0.0021)	0.006	0.002	0.006	0.006	0.001	0.003	0.006	0.006
(Average)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
MiuCrowd (SD = 0.0053)	0.02	0.015	0.02	0.02	0.005	0.015	0.02	0.02
(Average)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)	(0.017)
Parameters determined by site data								
Latitude	55.89	55.88	55.89	55.93	53.63	53.99	53.88	53.92
(Integralization)	(56.00)	(56.00)	(56.00)	(56.00)	(54.00)	(54.00)	(54.00)	(54.00)
Averaged temperature[c]	−3.579	−3.579	−3.579	−3.579	−1.373	−1.373	−1.373	−1.373
Wood C density (t C m^{-3}) [d]	0.19	0.23	0.22	0.22	0.19	0.23	0.22	0.22
Parameters from the literature or assumed								
Same as that in Table 3								

Note: values in parentheses are generalized parameters that were derived from the TRIPLEX calibration and they have been used for further simulations.
[a] Defined as in Table 2.
[b] SD represents standard deviation.
[c] AES, 1983.
[d] Newcomer, et al., 2000d.

son of two calibrations, the model accuracy can be estimated using generalized and non-generalized parameters. Our results show that accuracy can be achieved by using either the generalized parameters or the original parameters (Fig. 4). As shown in Fig. 4, after parameter generalization, the r^2 coefficients between observation and calibration are slightly decreased. The biggest difference of r^2 is only 0.15 ($0.93-0.78 = 0.15$) (Fig. 4F) between calibrations using the two different sets of parameters. Considering that a small decrease of r^2 is allowable, the generalized parameters (listed in parentheses in Table 4) are appropriate and utilizable in the TRIPLEX to further simulate additional plots or sites located in NSA and SSA.

3.3. Model validation and generality

Simulations using larger sample size ($n = 277$) collected from 66 independent sites located in NSA and SSA were conducted in terms of basal area, tree density, and above-ground biomass. The predictions were highly correlated to the field measurements (Fig. 5). Generalized parameters as listed in parentheses in Table 4 were used in the model simulations. However, the parameter (Stemprn) that affects growth rate (called $P_{f,s}$ in 3-PG; see Landsberg and Waring, 1997) of tree stems was adjusted for some plots depending on some specific site conditions, which concern very high or low tree density, very young or old age of tree, site quality, and so forth. Although the parameter of Stemprn is defined to describe the growth rate on physiological causes in the TRIPLEX, it can also be an indicator of site quality. A key question is how to estimate the growth rate for different site conditions so as to determine the parameter of Stemprn. Usually, understanding the difference of growth rate of each stand would be difficult in a wide area because of lack of data (e.g., site quality, soil nutrition, and tree height etc.), and yet disregarding the difference of stands could cause a big error that affects the model accuracy. An indirect method presented in this study is to analyze the relationship of tree density and DBH, by which the DBH is measured more easily than tree height at low cost. As no thinning is involved in boreal forests, tree density represents how large an area of wood land (or how much nutrition) is being occupied by a tree. That tree density decreases and DBH increases in a stand can describe the growth rate, including abnormal stands whether with or without the competition.

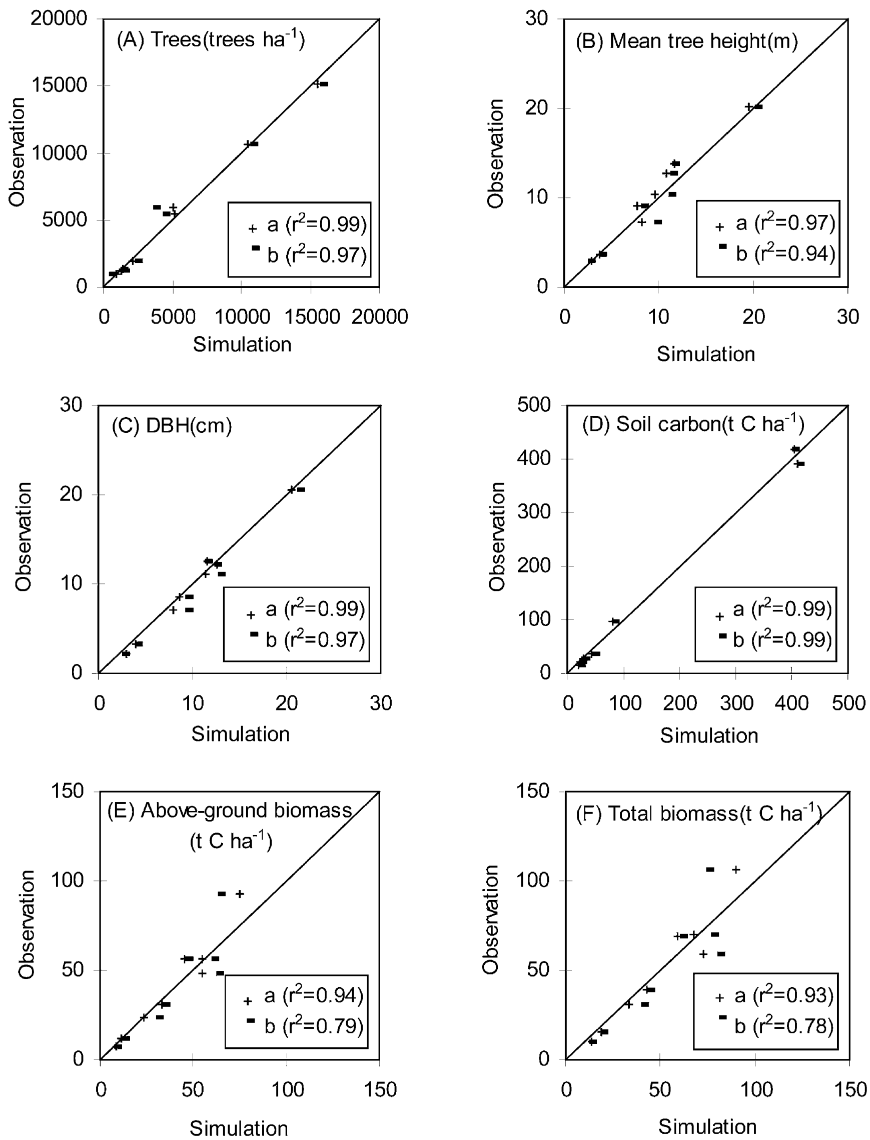

Fig. 4. Model calibration. Comparisons between simulated and observed (A) tree density (tree ha^{-1}), (B) Mean tree height (m), (C) diameter at breast height (DBH) (cm), (D) soil carbon (t C ha^{-1}), (E) above-ground biomass (t C ha^{-1}) and (F) total biomass (t C ha^{-1}). The calibrations were based on the parameters in Tables 3 and 4. The "a" and "b" represent the results generated by using original parameter values (e.g., parameters without parentheses in Table 4) and by using the generalization of parameters (e.g., in parentheses in Table 4), respectively. Solid diagonal is the 1:1 line.

Also, DBH is one of the biological indicators (measured by Newcomer et al., 2000b in BOREAS) related to tree age, soil water, and nutrition status.

When using DBH (or height) to estimate the growth rate for determining the parameter Stemprn, the best way is to classify tree age, if seeking a more accurate relationship between DBH and tree density. However, to simplify the procedure of data processing, in this study, the factor of tree age was not analyzed whereas the trend of tree age is given. Fig. 3 illustrates that tree density reflects largely the trend of tree age, which was consistent in the analysis based on the ecological data (Newcomer, et al., 2000 b,d) and growth yield data of northern Ontario (Plonski, 1974).

As discussed above, using parameters listed in Tables 3 and 4 and adjusted with Eq. (5), the simulation generated results are shown in Fig. 5 and Table 6. There are three linear regression functions describing the relationship between model simulation and observation for basal area, tree density and above-ground biomass, respectively. The coefficients of determination (r^2) are greater than 0.58, which indicates that the prediction will fit actual values to a great extent. It was found that r^2 for tree density was higher than biomass and basal area. The reasons may be attributed as follows. One was caused by simulation procedure, in which tree density was calculated simply by two empirical coefficients (normal mortality ratio and crowding mortality ratio) while

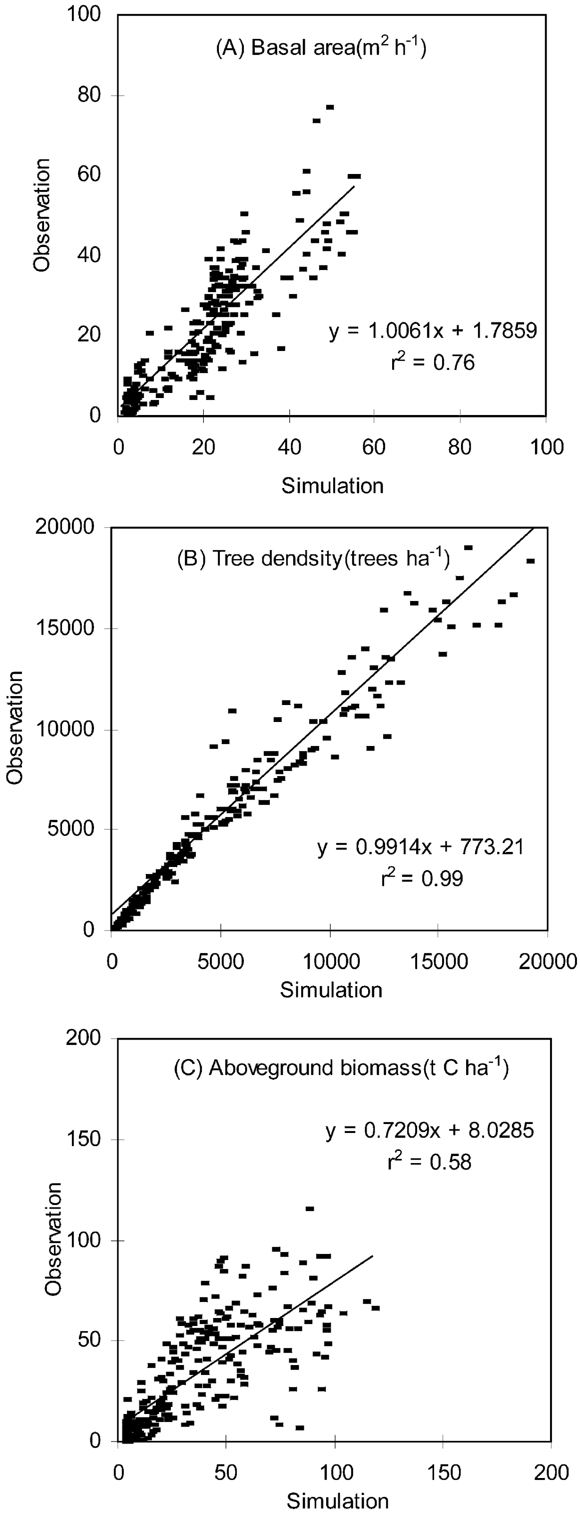

Fig. 5. Model validation. Comparison between observations and simulations for 66 independent BOREAS sites (Newcomer et al., 2000a,b). The TRIPLEX simulations were based on the parameters listed in Tables 2 and 3. Solid diagonal is the 1:1 line, and $n = 277$.

biomass and basal area were calculated by the process-based way with more parameters including some generalized parameters; another was due to the difference of measurement that results in a lower accuracy for biomass and basal area than tree density usually. Moreover, another problem may be related to heteroscedasticity in the regression. Some points far from the 45° line can cause a lower r^2. In further studies, besides examining initial model inputs closely, detecting heteroscedasticity is also needed for describing model validation comprehensively. As a reference, the comparison of simulation and observation for ANPP is presented in Table 5. Generalized parameters are used for simulations. The results (Table 5) show that the annual ANPP prediction based on 66 sites was comparable to the range of measured ANPP values derived from field data measured by Gower et al. (1997) in the same boreal forest region. In addition, our predicted ANPP are consistent with the observations (i.e., observed ANPP are 2.83, 2.03, 2.20 t C $ha^{-1}year^{-1}$ for aspen, black spruce and jack pine, respectively) collected from Alaska and Finland as well (Gower et al., 1997).

Testing the predictive ability of the TRIPLEX for nitrogen dynamics is a big challenge, because we often lack site specific observations of nitrogen. Table 5 shows a simple comparison of total nitrogen (t N ha^{-1}) between observations and simulations, which are within the ranges of observations. The soil nitrogen storage in other areas was reported in some literature as well as in the boreal forest region, and the one that also falls in the range of total soil nitrogen that is consistent with our simulations, approximately. For example, it ranges from 0.44 to 2.27 t N ha^{-1} (0–15 cm) in Lake Nipigon region of Canada (Hunt et al., 2001), and from 1.6 to 2.3 t N ha^{-1} (0–15 cm) in central Massachusetts of the USA (Compton et al., 1998). As seen in Table 6, the averages of our simulation were lower for black spruce and higher for jack pine than the averages of observations. This discrepancy may have resulted from using the same initial value for different species. The soil nitrogen contents of black spruce and jack pine need to be studied separately in the future.

4. Conclusions

The calibrations of the TRIPLEX were conducted to determine a set of suitable parameters and generalize those parameters for making the TRIPLEX practicable to boreal forest in a wider region. As a result of this case study, we have made model validation to examine the accuracy and generality of applying TRIPLEX for predicting carbon and nitrogen dynamics for major tree species of boreal forest ecosystem located in central Canada. The results of model validation suggest a reasonable and balanced parameter generalization pro-

Table 5
The comparison between observations and predictions of above-ground net primary productivity (ANPP, t C ha^{-1} $year^{-1}$) and total soil nitrogen (t N ha^{-1}). The observed values of ANPP (average level) and total soil nitrogen (in the top 30 cm) were obtained from Gower et al. (1997) and Newcomer et al. (2000a). The simulations of ANPP (mean) and total soil nitrogen (mean ± m.s.e.) were performed for NSA and SSA of BOREAS

	ANPP			Total nitrogen	
	NSA	SSA	Average	NSA and SSA	Average
Observation					
Aspen	3.49	3.52	3.51	–	–
Black spruce	1.36	1.66	1.51	1.10–5.45	2.89 ± 1.30
Jack pine	1.22	1.17	1.20	0.14–2.82	0.87 ± 0.65
Prediction					
Aspen	1.81	2.25	2.03	–	–
Black spruce	1.56	1.78	1.67	1.22–1.86	1.61 ± 0.17
Jack pine	1.13	1.71	1.42	1.29–1.98	1.68 ± 0.17

cedure that did not lead to a significant decrease of model accuracy, but did increase the model practicability. For further applying the TRIPLEX to a wider region of boreal forests or other forest ecosystems, including various natural or managed forest stands, this paper demonstrated a feasible approach to determine site-specific parameters related to forest growth rate by analyzing the relationship of tree density and DBH. The generalization of parameters used in this study also provides a promising approach for parameterizing and calibrating the TRIPLEX that can be used for simulating both short- and long-term carbon and nitrogen dynamics of boreal forest in NSA and SSA, as well as in other boreal regions in Canada.

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