Mitigation and Adaptation Strategies for Global Change (2007) 12: 525–543
DOI: 10.1007/s11027-006-4583-5

A SIMULATION OF TEMPORAL AND SPATIAL VARIATIONS IN CARBON AT LANDSCAPE LEVEL: A CASE STUDY FOR LAKE ABITIBI MODEL FOREST IN ONTARIO, CANADA

XIAOLU ZHOU[1,2,*], CHANGHUI PENG[2], QING-LAI DANG[1], JIAXIN CHEN[1]
and SUE PARTON[3]
[1]*Faculty of Forestry and the Forest Environment, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1*
[2]*Institut des sciences de L'environnement, Universite du Quebec a Montreal, Montreal, Canada, H3C 3P8*
[3]*Lake Abitibi Model Forest, Box 129, 143 Third Street, Cochrane, Ontario, Canada, P0L 1C0*
*(*Author for correspondence: E-mail: xiaolu.zhou@sympatico.ca, Tel: +1 (514) 987-3000, Ext. 3041)*

(Received 9 April 2004; accepted in final form 8 October 2004)

Abstract. Using a case study of the Lake Abitibi Model Forest (LAMF), this study aims to assess the temporal and spatial variability in carbon storage during 1990–2000, and to present a comprehensive estimation of the carbon budget for LAMF's ecosystems. As well, it provided the information needed by local forest managers to develop ecological and carbon-based indicators and monitor the sustainability of forest ecosystems. Temporal and spatial carbon dynamics were simulated at the landscape level using ecosystem model TRIPLEX1.0 and Geographical Information System (GIS). The simulated net primary productivity (NPP) and carbon storage in forest biomass and soil were compared with field data and results from other studies for Canada's boreal forests. The results show that simulated NPP ranged from 3.26 to 3.34 tC ha^{-1} yr^{-1} in the 1990s and was consistent with the range measured during the Boreal Ecosystem-Atmosphere Studies (BOREAS) in central Canada. Modeled NPP was also compared with the estimation from remote sensing data. The density of total above- and belowground biomass was 125.3, 111.8, and 106.5 tC ha^{-1} for black spruce, trembling aspen, and jack pine in the LAMF ecosystem, respectively. The total carbon density of forested land was estimated at 154.4 tC ha^{-1} with the proportion of 4:6 for total biomass and soil. The analysis of net carbon balance of ecosystem suggested that the LAMF forest ecosystem was acting as a carbon sink with an allowable harvest in the 1990s.

Keywords: Boreal forest, carbon modeling, ecosystem simulation, GIS application

1. Introduction

The boreal forest ecosystems play a significant role in the global carbon cycle and are sensitive to global climate change. Warming in the boreal ecosystem region may result in large-scale displacement and redistribution of boreal forests (Emanuel et al. 1985; Pastor and Post 1988; Neilson and Marks 1994), and the responses of the forest ecosystems will likely provide feedback about the climate. In Ontario, the forests and soils in the boreal region have large capacities to sequester and release carbon as they occupy about 62.66 Mha (e.g., 17% of Canada's forestland).

Recent carbon budget studies show that Ontario boreal ecosystems contain about 1.34 Pg biomass carbon, 9.76 Pg soil carbon, and release about 0.3 Pg carbon to the atmosphere in 1990 (Liu et al. 2002b). These carbon pools are sensitive to environmental conditions. For example, the organic carbon content of the biomass, forest floor, and mineral soil is the result of interactions between climate, succession, vegetation type, soil moisture, temperature, nutrient availability, soil texture, and disturbance regime (Banfield et al. 2002). Our quantitative understanding of these relationships and interactions, however, is inadequate, particularly for capturing carbon dynamics and spatial distributions.

During the past decade, the temporal dynamics and spatial distribution of carbon sequestration has been simulated in a numbers of studies for Canada's boreal ecosystems. They estimated aboveground biomass (Kurz et al. 1996a; Halliwell and Apps 1997a; Penner et al. 1997; Price et al. 1999; Kimball et al. 2000; Banfield et al. 2002; Foster and Morrison 2002), belowground biomass (Kurz et al. 1996b), NPP (Peng and Apps 1999; Kimball et al. 2000; Liu et al. 1997, 2002a; Chen et al. 2002, 2003), and soil carbon (Dixon et al. 1994; Halliwell et al. 1995; Nalder and Merriam 1995; Halliwell and Apps 1997b; Price et al. 1997, 1999; Siltanen et al. 1997; Lai et al. 1997; Peng et al. 1998). However, few studies estimated overall carbon dynamics and budget, which integrated all key variables (e.g., NPP, biomass, soil, and growth and yield) for describing complex interactions among each carbon pool. Moreover, most of the studies assessed NPP in stand level using scarce sampled stands (Gower et al. 1997; Ryan et al. 1997; Price et al. 1999) for describing stands at both temporal and spatial points, or in broad scale using remote sensing data (Chen et al. 2003; Liu et al. 1997, 2002a) for describing forests in a wide area. In practice, effective forest management requires an understanding of how carbon variations relate to different site variables at the management unit scale under an allowable harvest. Although some debate has occurred about whether the criterion for carbon cycle assessment is relevant at the local level (Griffin 2001), an accurate determination of the impacts of forest management on carbon dynamics at provincial or national scales will require the local level estimation. For example, three carbon-based indicators including NPP, tree and nontree biomass, and carbon budget have been developed for assessing the carbon cycle and dynamics by LAMF.

In this study, we performed an integrated simulation of temporal and spatial carbon dynamics at landscape level in the LAMF. The model used for simulating the boreal ecosystem of the LAMF is a generic hybrid model of TRIPLEX1.0, which involves key variables of ecosystem simulation such as photosynthetically active radiation (PAR), gross primary productivity (GPP), biomass, soil carbon, soil nitrogen, soil water, stand growth, and yield. GIS technology was used to prepare the data for initial inputs of the simulation model and integrate the temporal and spatial distributions for output variables. The climate data for each stand were interpolated using the downscale algorithm (Oelschlagel 1995), and the estimation period ranged from 1990 to 2000 with a monthly time step.

The aims of this study were to (1) assess the temporal and spatial variability in carbon storage; (2) present a comprehensive estimation of carbon budget for boreal ecosystems in the LAMF; and (3) provide information needed by local forest managers to develop ecological and carbon-based indicators to monitor the sustainability of forest ecosystems. This paper reports the descriptions and analysis of the productivity dynamics and climate effect, carbon density and spatial distribution at landscape level, and net carbon balance for the local region of LAMF. This study also provides a quantitative reference by developing carbon-based indicators for sustainable forest management at the local scale.

2. Materials and Methods

2.1. Study area

The LAMF is one of 11 model forests across Canada that was supported by the Canadian Model Forest Program. The Canadian Forest Service (CFS) initiated the Canadian Model Forest Network in 1992 to bring together a wide range of people and groups with interests in forests and sustainable forest management. The LAMF is located in the boreal forest of northeastern Ontario (Figure 1) and has a total area (land and water) of 1.2 million ha, and forestland area of 0.9 million ha, approximately. As shown in Figure 1, the LAMF is divided into two parts: Iroquois Falls North has a forestland area of 0.8 million ha and Iroquois Falls South has a forestland area of 0.1 million ha.

The physiography of the LAMF is dominated by the Great Northern Clay Belt. This area is relatively rolling, and the elevation ranges from 250 to 350 m above sea level. A large area dominated by glacial outwash includes primarily fine textured clay, covered by organic deposits in poorly drained areas (Environment Canada 2000; Griffin 2001). About 50% of the land in the LAMF is organic deposits or peatlands, with other areas covered by glacial landforms such as eskers, moraines, and drumlins. The climate of the LAMF and its associated weather are influenced by James Bay to the north (Environment Canada 2000). It is characterized by a humid-continental climate of short, cool to moderately warm summers and long, cold to severe winters.

2.2. Data

2.2.1. *Forest Stands*

In the LAMF, there were primarily eight dominant species listed as follows: trembling aspen (*Populus tremuloides*), jack pine (*Pinus banskiana*), black spruce (*Picea mariana*), black ash (*Fraxinus nigra*), balsam fir (*Abies balsamea*), cedar (*Thuja occidentalis*), larch (*Larix laricina*), and balsam poplar (*Populus balsamifera*). Tree ages ranged from 2 to 283 years in 2000, and were older in Iroquois Falls North

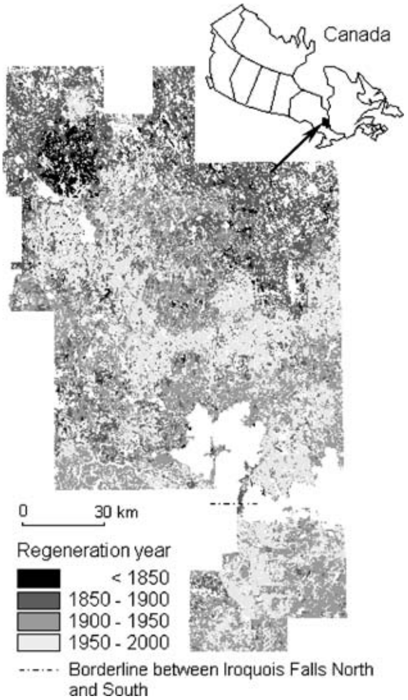

Figure 1. Location of the Lake Abitibi Model Forest (LAMF) and the distribution of the forest regeneration years.

than in Iroquois Falls South (see the regeneration year distribution in Figure 1 and age class structure in Figure 2). The vegetation data of the forest ecosystem are available in the LAMF, and were collected as the attribution data of GIS ArcView. The simulation requires a dataset on the stand level, such as tree species and site class for parameterization, and tree age and stocking for initialization. These data were compiled for every stand since the polygon in GIS spatial files corresponded to the forest stand.

2.2.2. *Disturbances*

The disturbance conditions affected the estimation of carbon budget in whole region. Some harvest occurred in the LAMF during the 1990s, with an annual allowable cut (AAC) of approximately 7 50 000 m^3. This AAC was converted from the allowable harvest area (Griffin 2001: approximately 8670 ha yr^{-1} and 0.11% of the total forest area in LAMF land) as described in the Forest Management Plan, which is renewable every 5 years. To ensure that harvested areas are successfully regenerated, regeneration activities were monitored based on the prescription that was developed for a specific harvest area. Regeneration success has increased significantly from 1985 to 2000 in the LAMF (Griffin 2001). Observations of forest

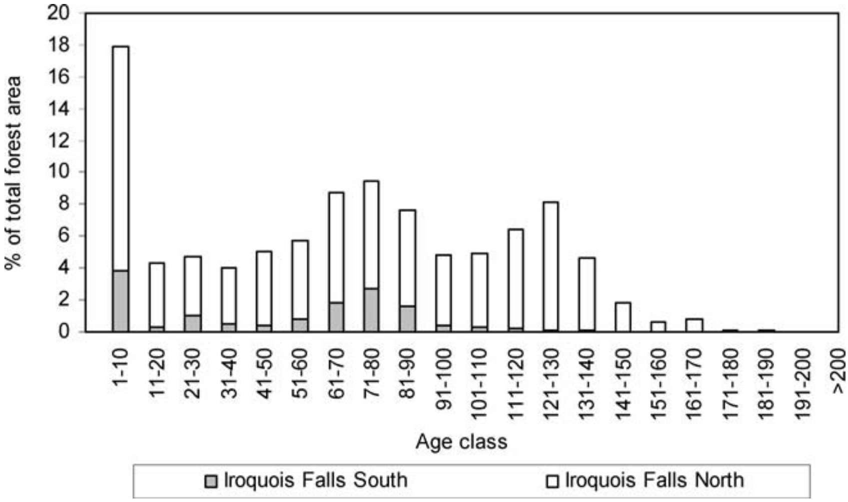

Figure 2. The percentage of total forest area in age class structure of LAMF. Field data was updated in 1994.

fire occurrence were obtained from the database constructed by Ontario Ministry of Natural Resources (OMNR). OMNR has produced a comprehensive database for all large fires (greater than 2 km^2) that occurred in Ontario since 1921 (Fleming et al. 2002).

2.2.3. *Soil Texture*

The soils in the LAMF are primarily fine textured clays, covered by organic deposits in poorly drained areas (Griffin 2001). These organic deposits or peatlands comprise more than 50% of LAMF area. There are also a number of glacial landforms such as eskers, moraines, and drumlins. Ontario Land Inventory and Primeland/Site Information System (Elkie et al. 2000) presented details of soils in Ontario forest ecoregions. The area proportions of soil composition in the LAMF are 65, 2, 16, 2, and 15% for clay, clay and medium sand, fine sand, medium sand, and unclassified, respectively.

2.2.4. *Climate Data*

The climate data used in this study were obtained from the Canadian Climate database (CCCma 2003). Average air temperature and precipitation are available at a spatial grid with a horizontal resolution of 3.75° × 3.71° (longitude × latitude). A downscaling technique was applied for resolving the finer features of the forest ecosystem that is sensitive to local climate, thereby obtaining representative values at the center points of each stand. We assumed values at centroid points represent averages of climate conditions in those stands. To downscale for the LAMF, only the four nearest grid points around the target location were used for the interpolation procedure that defined each variable on a spherical surface (reported by Oelschlagel

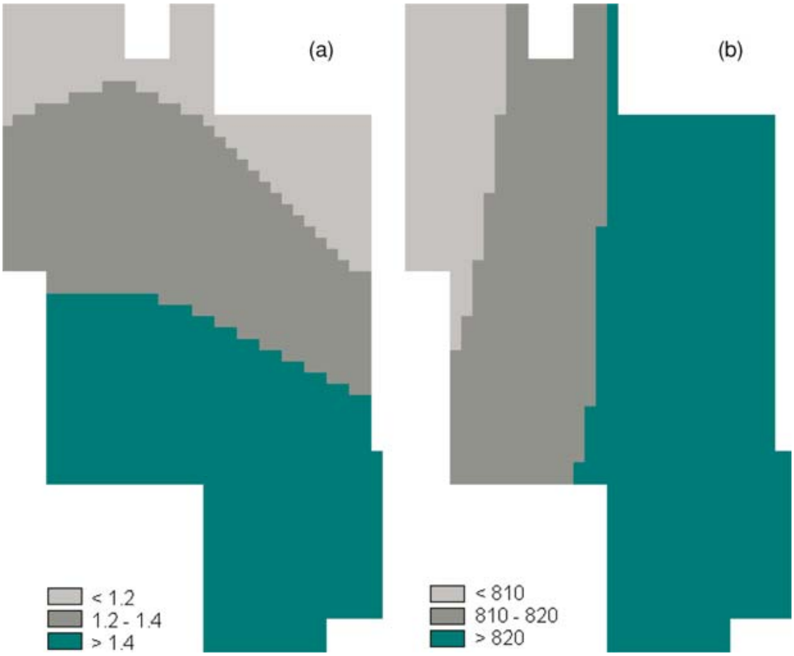

Figure 3. The annual temperature (°C) (a) and precipitation (mm) (b) downscaled for the LAMF in 1995.

1995). For air temperature and precipitation, the monthly average at every grid point was interpolated and the result was added to the average. Figure 3 illustrates the annual temperature and precipitation downscaled for 1995 as an example.

2.3. MODEL DESCRIPTION

The TRIPLEX1.0 (Peng et al. 2002) is a generic hybrid simulation model which combines advantages of both empirical and process-based models. This model was constructed for bridging the gap between empirical forest growth and yield and process-based carbon balance models. The simulation of the TRIPLEX1.0 involves key variables of forest ecosystem including PAR, GPP, forest growth, biomass, soil carbon, soil nitrogen, and soil water. All simulations were conducted with a monthly time step, while simulation output was summarized yearly. The structure of the TRIPLEX1.0 (Figure 4) includes the following four major components:

(1) Forest production. This submodel estimates photosynthetically active radiation (PAR), Gross Primary Productivity (GPP), and aboveground and belowground biomass. The PAR was calculated as a function of solar constant, radiation fraction, solar height, and atmospheric absorption. The initial PAR was estimated

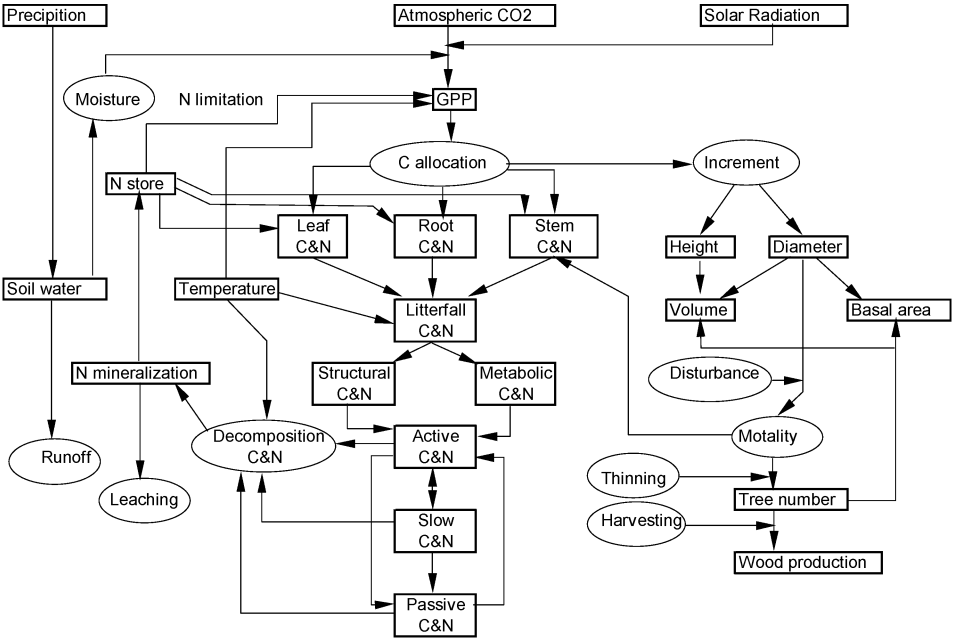

Figure 4. The structure of ecosystem simulation model TRIPLEX1.0 (modified from Peng et al. 2002).

as a solar constant (1360 Wm^{-2}) with the solar radiation fraction set at 0.47 (Bossel 1996). The solar height is calculated depending on the latitude of the site and the time of day. GPP was calculated monthly on the basis of received PAR, forest age, monthly mean air temperature, vapor pressure deficiency, soil drought, and percentage of frost days in the month. There is a fixed fraction ($C_{\text{NPP}} = 0.39$) suggested by Ryan et al. (1997) for estimating the proportion of NPP in GPP for boreal forest ecosystems. Carbon allocation was defined depending on the apportionment of carbon assimilation among the foliage, stem and root.

(2) A soil carbon and nitrogen submodel that simulates carbon and nitrogen dynamics in litter and soil pools. This part was based on CENTURY's soil decomposition submodel (Parton et al. 1987, 1993) that provides carbon and nitrogen mineralization rates for Canadian boreal forest ecosystems. The rate of soil carbon decomposition for each pool is calculated as a function of carbon stock for a particular pool, maximum decomposition rate, effects of soil moisture and temperature.

(3) Forest growth and yield submodel that calculates tree growth and yield variables (e.g., height, diameter, basal area, and volume). Annual increments of individual tree height are calculated as a function of stem wood biomass increment, tree diameter at breast height, height/diameter ratio, wood density, and

tree form factor. Height and diameter growth is influenced by a combination of physiological and morphological responses to environmental factors. Height to diameter ratio has been proposed as an alternative competition index to be used in determining the free growth status of the tree. Three assumptions proposed by Bossel (1996) were used for calculating tree height and DBH growth: (a) if crown competition is occurring, trees grow more in height; (b) if no crown competition, trees grow faster in diameter; and (c) carbon mass of an individual tree is estimated as a product of tree volume and the specific wood carbon density. The harvest processing represents clear cutting at the harvesting year in this study.

(4) Soil water balance submodel that simulates water balance and dynamics. This component incorporated the soil water submodel of CENTURY. It is a simplified water budget model that calculates monthly water loss through transpiration, evaporation, water content of soil, and snow water content. Water inputs are rainfall including snow; outputs are transpiration, evaporation, and leached water.

The TRIPLEX1.0 was been calibrated and validated for pure jack pine stands in Ontario (Peng et al. 2002; Liu et al. 2002c) and for major boreal tree species in central Canada (Zhou et al. 2004) before being applied to the LAMF. Considering that a large portion of LAMF is forested peatland, we noted that parameters calibrated for upland forest condition could produce the uncertainty associated with modeling some stands in the LAMF, especially in poorly drained stands and forested-peatland, in which NPP is usually less than those in upland forest (with same site index). The calibration for poorly drained stands was not conducted in this study because of insufficient field data. Primary parameters for this study are listed with their references in Appendix.

2.4. SIMULATIONS

The simulation was performed for NPP, above and belowground biomass, soil carbon as well as forest growth. We simulated every respective stand in LAMF from their regenerated year to 1990, 1995, and 2000, and then summed up the simulations across all stands in the LAMF. The growth condition of all stands before harvesting was estimated by mean density of harvested volume (109 m^3 ha^{-1}) and years to attain free-to-grow status after harvest (around 7 years, as reported by Griffin 2001). We assumed that the mean volume density (109 m^3 ha^{-1}) was cut 7 years earlier than the regenerated year for all regenerated stands (about 4828 ha yr^{-1} estimated according to field data). The landscape-level estimation was based on the simulation result of every stand, and was performed by converting stand-level maps to landscape images in 3 × 3 km grid cell using GIS (converting vector to raster map in ArcView).

The ecosystem carbon balance for the whole region was estimated based on simulation results compiled for 1990, 1995, and 2000. The carbon balance was calculated using the following equations:

$$\text{Net Carbon Balance (NCB)} = \text{Carbon uptake (NPP)} - \text{Carbon Release}$$

$$\text{Net Biome Productivity (NBP)} = \text{NCB} - \text{Carbon Loss by Harvesting}$$

"Carbon Release" includes carbon emissions by root heterotrophic respiration and soil decomposition, NPP accumulates the forest biomass over years and produces litterfalls that decompose and add the carbon to soil, and the annual harvest removes forest biomass from the ecosystem, resulting in a decrease of carbon stock. The harvested volume (from local data) was converted to carbon using wood carbon density (tC m^{-3}). We estimated NBP by subtracting the amount of harvested carbon from the amount of NPP and C release in the LAMF for each year.

3. Results and Discussions

3.1. NET PRIMARY PRODUCTIVITY

The simulation results show the average NPP was estimated as 3.26 (tC ha^{-1} yr^{-1}) for 1990, 3.28 (tC ha^{-1} yr^{-1}) for 1995, and 3.34 (tC ha^{-1} yr^{-1}) for 2000 in the LAMF forest ecosystem. Comparing simulated NPP with other studies, simulation values are consistent with the range estimated at stand level (2.16–3.92 tC ha^{-1} yr^{-1}, Gower et al. 1997) for NSA and SSA, and slightly higher than national level (3.08 tC ha^{-1} yr^{-1}, SD $= 1.15$, $n = 1272$, and $p < 0.00001$) for the LAMF (see Figure 5b, data from Liu et al. 2002a). The agreement of NPP spatial distribution between Figure 5a and 5b was simply estimated using the *Kappa* statistic, which measures the grid cell by grid cell agreement between the two maps (Cohen 1960; Monserud 1990). The *Kappa* value (0.55) suggests a good agreement of Figure 5a and 5b.

The simulated NPP values are also comparable to an average NPP of 3.65 tC ha^{-1} yr^{-1} as calculated by CBM-CFS2 for Ontario's boreal area (Liu et al. 2002b) and of 2.54–2.73 tC ha^{-1} yr^{-1} estimated by CENTURY 4.0 for BOREAS of central Canada (Peng and Apps 1999). Results indicate that the distribution of NPP for the LAMF at landscape level was within the range of 2.16–3.92 tC ha^{-1} yr^{-1} reported by Gower et al. (1997).

3.2. BIOMASS

The average of aboveground biomass density ranges from 80.8 to 95.2 (t ha^{-1}) for the studied area of the LAMF (see Table I) in 2000. For three major species, the aboveground biomass density of black spruce was 12 and 17% higher than aspen and jack pine, respectively. A comparison of observation and estimation shows that LAMF's aboveground biomass occurred within the reasonable range of 75–100 t ha^{-1} obtained from Canada's forest biomass resources (Penner et al. 1997)

TABLE I

Comparison of simulated aboveground biomass[a] (t ha^{-1}) with estimations and observations at landscape level

Black spruce	Trembling aspen	Jack pine	Reference
95.2	84.9	80.8	Simulated using TRIPLEX1.0 in this study
91.1	80.8	73.3	[b]Newcomer et al. 2000
75–100 (all species)			[c]Penner et al. 1997.

[a] Total biomass was estimated as 125.3, 111.8, and 106.5 t ha^{-1} for black spruce, trembling aspen, and jack pine in 2000, respectively.

[b] Observations from the field data of BOREAS, central Canada including southern study area (SSA) and northern study area (NSA).

[c] Estimated for LAMF region, data from the 1994 Canadian Forest Inventory.

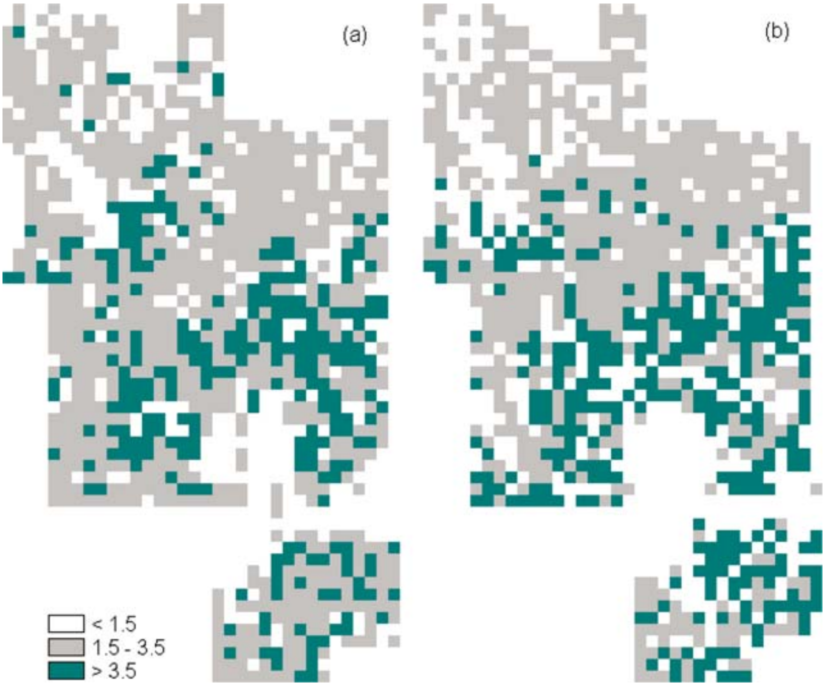

Figure 5. The comparison between NPP (tC ha^{-1} yr^{-1}) simulations at landscape (a) and remote sensing (b) levels for the LAMF (Kappa value $K = 0.55$). Monserud (1990) and Prentice et al. (1992) used the following qualitative descriptors to characterize the degree of agreement suggested by the Kappa statistic: very poor to poor agreement if $K < 0.4$, fair agreement if $0.4 < K < 0.55$, good agreement if $0.55 < K < 0.7$, very good agreement if $0.7 < K < 0.85$, and excellent agreement if $K > 0.85$. (a) was based on the TRIPLEX model simulation for 1995 and (b) was converted using spatial data from Liu et al. (2002a) for 1994 . The grid size is 3 × 3 km.

TABLE II

Comparison of simulated soil carbon density (tC ha^{-1}) for the LAMF in 2000 with measurements and estimations at landscape level

Average soil C density	Method	References
Simulation		
93.9 (28.3)	TRIPLEX1.0, LAMF, Boreal East	This study
72.7 (20.3)	CENTURY4.0, Central Canada	Peng et al. 1998
80–95	CBM-CFS, Boreal West[a]	Price et al. 1997
70–85	Q_{ff} and Q_m, Boreal Eest[a]	Tremblay et al. 2002
Measurement		
111.2 (56)	Soil C is to 100 cm depth, Boreal East	Siltanen et al. 1997
81.2 (47)	Soil C is to 100 cm depth, Boreal West	Siltanen et al. 1997
118.0 (15)	Boreal West	Kurz et al. 1992
113.9 (54.1)	Soil C is to 100 cm depth, Central Canada	Halliwell and Apps 1997b

Note. Values in parentheses denote standard deviations of cited carbon values.
[a] Caegorized for ecoclimatic regions of Canada.

for aboveground biomass in boreal forest ecosystems. The average aboveground biomass density (91.9 t ha^{-1}) in the LAMF is slightly higher than the range (73.3–91.1 t ha^{-1}) in central Canada (Newcomer et al. 2000) and the average (86 t ha^{-1}) in boreal west (Banfield et al. 2002), since differences exist among boreal east (LAMF), west and central areas. The understory biomass was not calculated independently because of its small proportion, e.g., less than 1% of total biomass calculated by Gower et al. (1997). Spatial distributions of biomass density (Figure 6) illustrate that the biomass density is generally higher in Iroquois Falls North than in Iroquois Falls South.

The dynamics of belowground biomass were also simulated for LAMF ecosystems. The belowground biomass was calculated for coarse roots greater than 5 mm, and fine roots less than and equal to 5 mm (Ryan et al. 1997; Steele et al. 1997). Generally speaking, a tendency for belowground biomass is that different sites affect the proportion of aboveground and belowground biomass; for example, some roots grow well in poor soil, such as sandy, arid, or lower site class. Our simulation reveals the different proportion of belowground to total biomass (t ha^{-1}) by site class (Figure 7), and the results show that black spruce has a higher proportion of belowground biomass than jack pine and trembling aspen.

3.3. SOIL CARBON

Total soil carbon in the LAMF is estimated at 83.7 Mt C in 2000, and average soil carbon density is 93.9 tC ha^{-1} approximately (Table II). All estimations of soil carbon in this study are limited for forestlands only, which do not include lakes,

Figure 6. Distributions (grid size is 3 × 3 km) of total biomass density (t ha^{-1}) including above- and belowground for the LAMF in 2000.

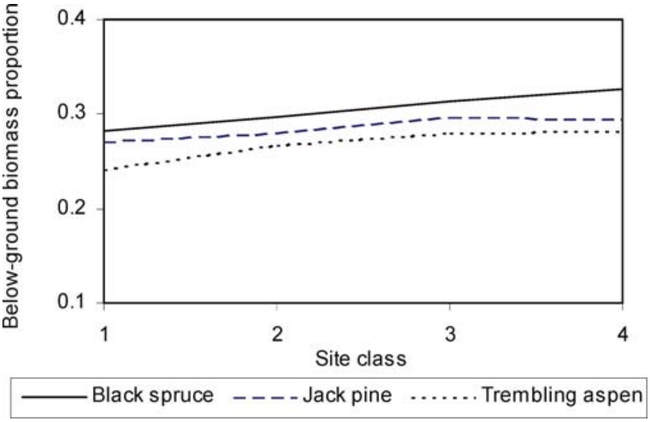

Figure 7. Simulated proportion of belowground to aboveground biomass in the LAMF for 2000, simulated using TRIPLEX1.0.

TABLE III

The dynamics of carbon stocks and balance in LAMF's forest ecosystem

Variable	1990	1995	2000
Total C stock (Mt C)	132.4	135.8	139.2
Biomass C stock (Mt C)	48.3	52.0	55.5
Soil and Litter C stock (Mt C)	84.1	83.8	83.7
C uptake (total NPP) (Mt C yr^{-1})	2.92	2.94	3.00
Harvesting (Mt C yr^{-1})	0.13	0.14	0.12
C release (Mt C yr^{-1})	0.94	0.95	0.96
Net C balance (Mt C yr^{-1})	1.98	1.99	2.04

Note. Each variable was calculated only for three separated years (e.g., 1990, 1995, and 2000).

rivers, and any nonforestlands. The contribution of soil carbon to total ecosystem carbon, which includes aboveground biomass, belowground biomass, detritus, and soil carbon, was estimated and compared with two age class groups. Results indicate that an average soil carbon contributes approximately 60% of total ecosystem carbon for all age stands. Younger stands (<100 years) had a higher percentage (around 66%) whereas older stands (>100 years) were lower (around 51%) in the LAMF because younger stands have less biomass carbon than older stands. The total forest ecosystem carbon (including vegetation, detritus, and soil) content was 154.4 tC ha^{-1} with about 60% of the carbon (93.9 tC ha^{-1}) in soil and litter. This means that the proportion (about 2:1) of soil and aboveground biomass carbon (46.0 tC ha^{-1}) supports our analysis of the field data from BOREAS (Newcomer et al. 2000) and other available databases (Siltanen et al. 1997, CLBRR 1993, ORNL 2002) of boreal ecosystems. This proportion was also reported by Peng et al. (1998) and Price et al. (1999) in their model simulation studies for boreal ecosystems in central Canada. Since we do not have the point by point field measurements of soil carbon for the entire LAMF, we used the existing national soil carbon database as a general reference to verify our model simulations. As references for an overview, Table II compares the soil carbon density with other recent studies for Canada's boreal region. The soil carbon density ranges from 81.2 to 118.0 tC ha^{-1} for field measurements and 70–95 tC ha^{-1} for model simulations. Our simulation agrees with in both observed and simulated ranges.

Generally, litterfalls return carbon from biomass carbon stocks to soils, and different stand age and tree species determine the soil carbon flux. Based on the simulation, we noticed few differences in soil carbon between the stands with different tree species; however, we did not compare them with observations in this study because of insufficient necessary data on soil details such as soil nutrient, layer depth, and moisture. We also found no significant variation of soil carbon in the LAMF during the period from 1990 to 2000, although climate condition was changing. It implies that soil carbon was relatively stable in the LAMF if there were few or no intensive disturbances (e.g., neither large harvest cutting nor forest fire) that can cause the change of soil carbon flux and result in a variation of soil carbon pool.

3.4. NET CARBON BALANCE

To summarize each carbon pool and flux for entire region of the LAMF, net carbon balance was estimated for the LAMF (Table III). Figure 8 illustrates the carbon budget of the LAMF for 2000. The net carbon balance (NCB) reached 2.04 Mt C yr^{-1}, and NBP was estimated about 1.92 Mt C yr^{-1}, which represents net carbon gain after harvesting. The total biomass C stocks were estimated to be 40% of total carbon stock in the LAMF forest ecosystems. Aboveground biomass was about 76% of total biomass carbon. The carbon content of harvesting was converted from local data of the LAMF using average wood carbon density, which was reported by Zhou et al. (2004) as 0.22 tC m^{-3} (0.19, 0.23, and 0.22 for trembling aspen, black spruce, and jack pine, separately).

In Figure 8, biomass and soil carbon stocks were estimated before harvesting, but we did not take into account the effect of forest fire on carbon balance in this study since forest fires did not occur frequently in the LAMF during the 1990–2000. For example, the average total burn area covered only 0.38% of the area of the LAMF in the 1990s. This implies that carbon released from the ecosystem by forest fires had a relatively small impact on carbon balance of LAMF ecosystems. Also, the current formation of the TRIPLEX model does not include the fire simulation module that will be incorporated into the new version of TRIPLEX in next step.

Although there was a large carbon source in Ontario's forest ecosystems (−31 Mt C) estimated for 1990 by Peng et al. (2000), the simulation shows that LAMF forest ecosystem was acting as a carbon sink in the 1990s (NCB was around 2 Mt C from 1990 to 2000), mainly due to most of younger stands (average stand

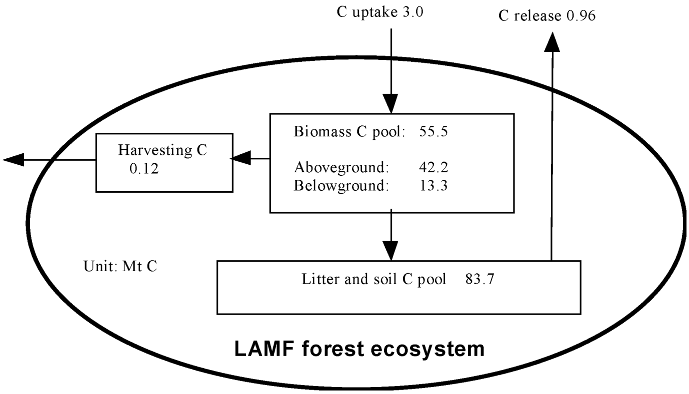

Figure 8. The carbon budget of LAMF forest ecosystem in 2000. Net carbon balance (NCB) and net biome productivity (NBP) were 2.04 Mt C and 1.92 Mt C yr^{-1}, respectively.

age was 72 years) with higher productivity, and very few disturbances (e.g. forest fire) occurred in LAMF in the 1990s. Generally speaking, immoderate forest harvest did affect the carbon budget of an ecosystem. The approach taken with this study can be applied to the evaluation of carbon balance and harvest effects in temporal and spatial ranges. In the LAMF, for example, harvested carbon contents did not affect net carbon balance significantly. Our results indicated that harvested carbon was only 4% of NPP in every year during the 1990's, due to the limit of allowable harvest (7 50 000 m^3 yr^{-1}) in the LAMF from 1990 to 2015, and that actual total harvested volume has been lower than the allowable level from 1990 to 2000 (approximately 6200 ha annually, 0.08% of total LAMF forestland).

This study was limited not only by the availability of field data but also by the current version of the TRIPLEX 1.0 model. To predict the effects of future climate change, the CO_2 concentration needs to be considered, and impacts of ecosystem disturbances and forest management regimes should be taken into account. New modules, including forest harvest and fire should also be developed. These disturbance processes will be incorporated into the new version of the TRIPLEX 1.0 model. In addition, since the TRIPLEX 1.0 model utilized a monthly time step, the simulation for daily carbon flux is limited and would be improved through ongoing projects and the Fluxnet-Canada Network (Fluxnet-Canada 2002).

4. Conclusions

The TRIPLEX1.0 simulations of carbon dynamic are consistent with the estimations based on observations and inventory data of NPP, biomass, and soil carbon for Ontario's boreal ecosystems. The carbon density of forestland was estimated at a level of 150 (tC ha^{-1}) approximately, with the proportion (4:6) of total biomass, and soil. The NPP (3.26–3.34 tC ha^{-1} yr^{-1}) in the LAMF of north Ontario was estimated between observed values of NSA and SSA in central Canada. The results presented here suggest that temporal dynamics of biomass and NPP were increasing in LAMF in the 1990s. Our results show that because of younger stands and few disturbances occurred in the LAMF, the LAMF forest ecosystem was acting as a carbon sink in the 1990s, in opposition to the large carbon source in Ontario's forest ecosystems. In this study, we demonstrated one application of the TRIPLEX 1.0 model to investigate biomass dynamics, NPP increment, soil carbon, and net carbon balance in the LAMF area. Results will be useful for local forest managers to develop ecologically sound indicators for monitoring the sustainability of forest ecosystems, and to make more informed management decisions.

Acknowledgments

The funding for this project was supported by Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), Canada Research Chair Program, The Lake

Abitibi Model Forest (LAMF) Program, as well as partially supported by the Ontario Ministry of Natural Resources through the Ontario Government Climate Change Fund for the TRIPLEX1.0 development. We thank D. Schultz and J. Candau for providing GIS data and their useful suggestions, and J.M. Chen and W. Ju for providing the remote-sensing-based NPP estimations for LAMF. We also thank Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) for providing field data of Boreal Ecosystem-Atmosphere Study (BOREAS). We are also grateful to G. Stanclike for his assistance with this project. The postdoctoral fellowship to X. Zhou by Lakehead University is greatly appreciated.

Appendix: Primary Parameters Used

Parameter	Description	References
Tveg = 5	Temperature of vegetation begin and end	Bossel 1996
Sla = 6	Specific leaf area	Kimball et al. 1997
Topt = 15	Optimum temperature for producing GPP	Kimball et al. 1997
Ccpp = 0.39	Convert GPP to NPP	Ryan et al. 1997
Cloud = 0.4	Cloud ratio for a month	Bossel 1996
AlphaC = 0.05	Canopy quantum efficiency	Landsberg and Waring 1997
GamaS = 0	Stem loss ratio	Assumption
Lnr = 0.26	Lignin–nitrogen ratio from N Module	Parton et al. 1993[a]
K1-K8	Max decomposition rate in soil	Parton et al. 1993[a]
A1 = 15	Soil water depth of layer 1 (cm)	Parton et al. 1993
A2 = 15	Soil water depth of layer 2 (cm)	Parton et al. 1993[a]
A3 = 15	Soil water depth of layer 3 (cm)	Parton et al. 1993
AWL1 = 0.5	Relative root density (layer 1)	Parton et al. 1993[a]
AWL2 = 0.3	Relative root density (layer 2)	Parton et al. 1993[a]
AWL3 = 0.2	Relative root density (layer 3)	Parton et al. 1993[a]
KF = 0.5	Fraction of H_2O flow to stream	Assumption
KD = 0.5	Fraction of H_2O flow to deep storage	Assumption
KX = 0.3	Fraction of deep storage water to stream	Assumption
CD = 25	Crown to stem diameter ratio	Bossel 1996
AgeMax = 200	Maxmum tree age to grow	Assumption
MiuNorm = 0.002	Normal mortality ratio (yearly)	Bossel 1996[b]
MiuCrowd = 0.02	Crowding mortality ratio (yearly)	Bossel 1996
FR = 0.21	Root loss ratio (yearly)	Steele et al. 1997
MaxGama = 0.01	Max foliage loss ratio (yearly)	Gower et al. 1997[c]

[a] The values are given by CENTURY.

[b] Stand mortality was assumed as the normal mortality (no canopy competition for light) plus crowding mortality.

[c] Estimated on the basis of results (0.069–0.083 yr^{-1} in southern BOREAS area).

References

Banfield, G.E., Bhatti, J.S., Jiang, H. and Apps, M.J.: 2002, 'Variablility in regional scale estimates of carbon stocks in boreal forest ecosystems: Results from West-Central Alberta', *Forest Ecology and Management* **169**, 15–27.

Bossel, H.: 1996, 'TREEDYN3 Forest Simulation Model', *Ecological Modelling* **90**, 187–227.

CCCma: 2003, *Canadian Centre for Climate Modelling and Analysis*, Environment Canada, Meteorological service of Canada, CGCM2 Data (zip files). Available at http://www.cccma.bc.ec.gc.ca/cgi-bin/data [cited 2 July 2003].

Chen, J.M., Liu, J., Leblanec, S.G., Lacaze, R. and Roujean, J.: 2003, 'Multi-angular optical remote sensing for assessing vegetation structure and carbon absorption', *Remote Sensing of Environment* **84**, 516–525.

Chen, J.M., Pavlic, G., Brown, L. and Cihlar, J.: 2002, 'Derivation and validation of Canada-wide coarse-resolution satellite imagery and ground measurements', *Remote Sensing of Environment* **80**, 165–184.

CLBRR: 1993, *Soil Carbon Data for Canadian Soils*, CLBRR Contribution No. 92–179, Centre for Land and Biological Resources Research, Ottawa, Canada.

Cohen, J.: 1960, 'A Coefficient of agreement for nominal scales', *Educational and Psychological Measurement* **20**, 37–46.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C. and Wisniewski, J.: 1994, 'Carbon pools and flux of global forest ecosystems', *Science* **263**, 185–189.

Elkie, P.C., Towill, W.D., Ride, K.R. and Mcllwrath, D.L.: 2000, *Ontario Land Inventory Primeland/Site Information System* (*OLIPIS*), Ontario Mineral Natural Resources Northwest Science & Technology, Thunder Bay, Ontario, Canada, NWST Technical Manual TM-005.

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

Environment Canada: 2000, *Narrative Descriptions of Terrestrial Ecozones and Ecoregions of Canada: Boreal Shield Ecozone*, Environment Canada, Ottawa, Canada.

Fleming, R.A., Candau, J. and McAlpine, R.S.: 2002, 'Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada', *Climatic Change* **55**, 251–272.

Fluxnet-Canada: 2002, *Fluxnet-Canada research network: Influence of climate and disturbance on carbon cycling in forest and pratland ecosystems*. Available at http://www.fluxnet-canada.ca/home.php?page = home& setLang = en [cited 5 April 2004].

Foster, N.W. and Morrison, I.K.: 2002, 'Carbon sequestration by a jack pine stand following urea application', *Forest Ecology Management* **169**, 45–52.

Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J. and Stow, T.K.: 1997, 'Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada', BOREAS special issue, *Journal of Geophysical Research* **102**(24D), 29029–29041.

Griffin, T.: 2001, *Lake Abitibi Model Forest Local Level Indicator Status Report: 2000*, Lake Abitibi Model Forest, Ontario, Canada.

Halliwell, D.H. and Apps, M.J.: 1997a, *Boreal Ecosystem-Atmosphere Study* (*BOREAS*) *Biometry and Auxiliary Sites: Overstory and Understory Data*, Northern Forestry Centre, Edmonton, Canada.

Halliwell, D.H. and Apps, M.J.: 1997b, *Boreal Ecosystem-Atmosphere Study* (*BOREAS*) *Biometry and Auxiliary Sites: Soils and Detritus Data*, Northern Forestry Centre, Edmonton, Canada.

Halliwell, D.H., Apps, M.J. and Rice, D.T.: 1995, 'A survey of the forest site characteristics in a transect through the central Canadian boreal forest', *Water Air and Soil Pollution* **82**, 275–270.

Kimball, J.S., Keyser, A.R., Running, S.W. and Saatchi, S.S.: 2000, 'Regional assessment of boreal forest productivity using an ecological process model and remote sensing parameter maps', *Tree Physiology* **20**, 761–775.

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

Kurz, W.A., Apps, M.J., Comeau, P.G. and Trofymow, J.A.: 1996a, *The Carbon Budget of British Colombia's Forests, 1920–1989: Preliminary Analysis and Recommendations for Refinements*, Canada, FRDA Report No. 261, pp. 1–62.

Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J.: 1992, *The Carbon Budget of the Canadian Forest Sector: Phase 1*, Northern Forestry Centre, Edmonton, Canada, Forestry Canada Information Report, NOR-X-326.

Kurz, W.A., Beukema, S.J. and Apps, M.J.: 1996b, 'Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector', *Canadian Journal of Forest Research* **26**, 1973–1979.

Lai, R., Kimble, J.M., Follett, R.F. and Stewart, B.A.: 1997, *Soil Processes and the Carbon Cycle*, Chap. 7, Boca Raton, FL, CRC Press, pp. 93–101.

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

Liu, J., Chen, J.M., Cihlar, J. and Park, W.M.: 1997, 'A process-Based based Ecosystem ecosystem productivity simulator using remote sensing inputs', *Remote Sensing of Environment* **62**, 158–175.

Liu, J., Chen, J.M., Cihlar, J. and Chen, W.: 2002a, 'Net primary productivity mapped for Canada at 1 km resolution', *Global Ecology and Biogeography* **11**, 115–129.

Liu, J., Peng, C., Apps, M.J., Dang, Q., Banfield, E. and Kurz, W.: 2002b, 'Historic carbon budgets of Ontario's forest ecosystems', *Forest Ecology Management* **169**, 103–114.

Liu, J., Peng, C., Dang, Q., Apps, M.J. and Jiang, H.: 2002c, 'A component Objective Model Strategy for Reusing Ecosystem Models', *Computers and Electronics in Agriculture* **35**, 17–33.

Monserud, R.A.: 1990, *Methods for Comparing Global Vegetation Maps*, Working Paper WP-90-40, International Institute of Applied Systems Analysis, Laxenburg, Austria, pp. 5–21.

Nalder, I.A. and Merriam, H.G.: 1995, 'Simulating carbon dynamics of the boreal forest in Pukaskwa National Park', *Water Air and Soil Pollution* **82**, 283–298.

Neilson, R.P. and Marks, D.: 1994, 'A global perspective of regional vegetation and hydrologic sensitivities from climatic change', *Journal of Vegetation Science* **5**, 715–730.

Newcomer, J., Landis, D., Conrad, S., Curd, S., Huemmrich, K., Knapp, D., Morrell, A., Nickeson, J., Papagno, A., Rinker, D., Strub, R., Twine, T., Hall, F. and Sellers, P.: 2000, *Collected Data of the Boreal Ecosystem-Atmosphere Study*, CD-ROM, TE-06, The BOREAS Information System NASA Goddard Space Flight Centre, USA.

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

ORNL: 2002, *Global Soil Data Products*, Oak Ridge National Laboratory, Oak Ridge, TN.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S.: 1987, 'Analysis of factors controlling soil organic matter levels in Great Plains grasslands', *Soil Science Society of America Journal* **51**, 1173–1179.

Parton, W.J., Scurlock, J.M., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J-C., Seastedt, T., Garcia Moya, E., Apinan, K. and Kinyamario, J.I.: 1993, 'Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide', *Global Biogeochemical Cycles* **7**(4), 785–809.

Pastor, J. and Post, W.M.: 1988, 'Response of northern forests to CO2-induced climate change', *Nature* **334**, 55–58.

Peng, C. and Apps, M.J.: 1999, 'Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes', *Ecological Modelling* **122**, 175–193.

Peng, C., Apps, M.J. and Price, D.T.: 1998, 'Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in central Canada, 1. Model testing', *Global Biogeochemical Cycles* **12**, 381–402.

Peng, C., Liu, J., Apps, M., Dang, Q. and Kurz, W.: 2000, *Quantifying Ontario's Forest Carbon Budget* (*1. Carbon Stocks and Fluxes of Forest Ecosystems in 1990*), Forest Research Report No. 158, Ontario Forest Research Institute, Canada.

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

Penner, M., Power, K., Muhairwe, C., Tellier, R. and Wang, Y.: 1997, *Canada's Forest Biomass Resources: Deriving Estimates from Canada's Forest Inventory*, Information report BC-X-370, Pacific Forestry Centre, Victoria, Canada.

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

Price, D.T., Halliwell, D.H., Apps, M.J., Kurz, W.A. and Curry, S.R.: 1997, 'Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit', *Canadian Journal of Forest Research* **27**, 2005–2016.

Price, D.T., Peng, C., Apps, M.J. and Halliwell, D.H.: 1999, 'Simulating effects of climate change on boreal ecosystem carbon pools in central Canada', *Journal of Biogeography* **26**, 1237–1248.

Ryan, M.G., Lavigne, M.B. and Gower, S.T.: 1997, 'Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate', BOREAS special issue, *Journal of Geophisical Research* **102**(D24), 28871–28883.

Siltanen, R.M., Apps, M.J., Zoltai, S.C., Mair, R.M. and Strong, W.L.: 1997, *A Soil Profile and Organic Carbon Data Base for Canadian Forest and Tundra Mineral Soils*, Northern Forestry Centre, Canadian Forest Service, Edmonton, Canada.

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

Tremblay, S., Ouimet, R. and Houle, D.: 2002, 'Prediction of organic carbon content in upland forest soils of Quebec, Canada', *Canadian Journal of Forest Research* **32**, 903–914.

Zhou, X., Peng, C. and Dang, Q.: 2004, 'Assessing the generality and accuracy of the TRIPLEX model using in situ data of Boreal Forests in Central Canada', *Environmental Modelling and Software* **19**, 35–46.