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<u>Project Title:</u>

Quantifying the Impacts of Managed Disturbance Regimes on Carbon Stocks and Fluxes in Eastern Boreal Forests of Canada

<u>The Title of Project Final Report:</u>

Quantifying Temporal and Spatial Variations of Carbon Stocks and Fluxes at Lake Abitibi Model Forest in Ontario, Canada

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Executive Summary

The aim of this study was to assess the temporal and spatial variability in carbon storage, present a comprehensive estimation of carbon budget for the boreal ecosystems in Lake Abitibi Model Forest (LAMF) in Ontario, Canada. It provided gap information needed for local forest managers to develop ecological and carbon-based indicators and monitor the sustainability of forest ecosystems. The simulations of temporal and spatial carbon dynamics at landscape level were performed using the ecosystem model TRIPLEX1.0 and GIS (Geographical Information System). The simulated carbon storage, such as net primary productivity (NPP), forest biomass and soil carbon were compared with field data and results from other studies for Canada's boreal forests. The results show that the NPP ranged from 3.26 to 3.34 tC $ha^{-1}yr^{-1}$ in the 1990s and was sensitive to the changes in annual temperature and precipitation. The simulated NPP were consistent with the range measured during the Boreal Ecosystem-Atmosphere Studies in central Canada. The density of total above- and below-ground biomass was 125.3, 111.8, and 106.5 tC ha^{-1} for black spruce, trembling aspen, and jack pine, respectively. The total carbon density of forested land was estimated at 154.4 (tC ha^{-1}) with the proportion of 4:1 for above- and below-ground biomass and 4:6 for total biomass and soil. The estimation of carbon on the stand features (tree age, species, soil type, and site class) and the analysis of the net carbon balance suggest that the LAMF forest ecosystem was acting as a carbon sink in the 1990s.

Key words: ecosystem simulation, carbon modeling, boreal forest, GIS application.

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1. Introduction

The boreal forest ecosystems play a significant role in the global carbon cycle and are sensitive to global climate change. The warming in the boreal ecosystem region may result in large-scale displacement and redistribution of boreal forests (Emanuel et al. 1985, Pastor and Post 1998, Neilson and Marks 1994), and the responses of the forest ecosystems will likely feedback on the climate. In Ontario, the forests and soils in the boreal region have large capacities both to store and release carbon as they occupy about 17% of Canada's forest land. Recent carbon budget studies showed that Ontario boreal ecosystems contain 79% of biomass carbon, 89% of soil carbon, and 85% of carbon releases in whole region of Ontario (Liu et al. 2002b). Such vast carbon reservoirs consist of carbon pools that highly connect to each other in ecosystems. These carbon pools are affected by 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 above-ground 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), below-ground biomass (Kurz et al., 1996b), NPP (Peng and Apps, 1999; Kimball et al., 2000; Liu et al., 1997 and 2002a; Chen et al. 2002 and 2003), and soil carbon (Kurz et al., 1992 and 1996a; Dixon et al., 1994; Halliwell et al., 1995; Nalder and Merriam, 1995; Halliwell and Apps, 1997b; Siltanen et al., 1997; Lai et al., 1997; Peng, 1998; Price et al., 1999). However, there are few studies that estimated overall variables of carbon dynamics and budget. Because of the complex interactions among each carbon pool, the integrated simulation is expected to systematically explain boreal ecosystems. Moreover, most of the studies assessed NPP in stand level using scarce sampled stands (Gower et al, 1998; Ryan et al., 1998; 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 and 2002a) for describing forests in a wide area. In practice, the forest management requires to understand how the carbon variations relate to different site variables at the management unit scale.

In this study, we performed an integrated simulation of temporal and spatial carbon dynamics at landscape level in LAMF. The model used for estimating the boreal ecosystem of the LAMF is a generic hybrid model of TRIPLEX1.0, which involves key processes of ecosystem simulation such as photosynthetically active radiation (PAR), gross primary productivity (GPP), biomass, soil carbon, soil nitrogen, and soil water. This model has recently been calibrated and tested using the field measurements collected in Ontario (Peng et al., 2002) and in central Canada (Zhou et al., 2003). 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 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 LAMF; and (3) provide the gap information needed for local forest managers to develop ecological and carbon-based indicators and monitor the sustainability of forest ecosystems. This paper reports the descriptions and analyses of the productivity dynamics and climate effect, carbon density and spatial distribution at landscape level, and net carbon balance in the local region. It also provides the quantitative reference for the practice of forest management and planning 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 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 hectares, and forest land area of 0.9 million hectares approximately. As shown in Figure 1, the LAMF is divided by Iroquois Falls into two parts: the part of Iroquois Falls North has forest land area of 0.8 million hectares, and Iroquois Falls South has 0.1 million hectares approximately.

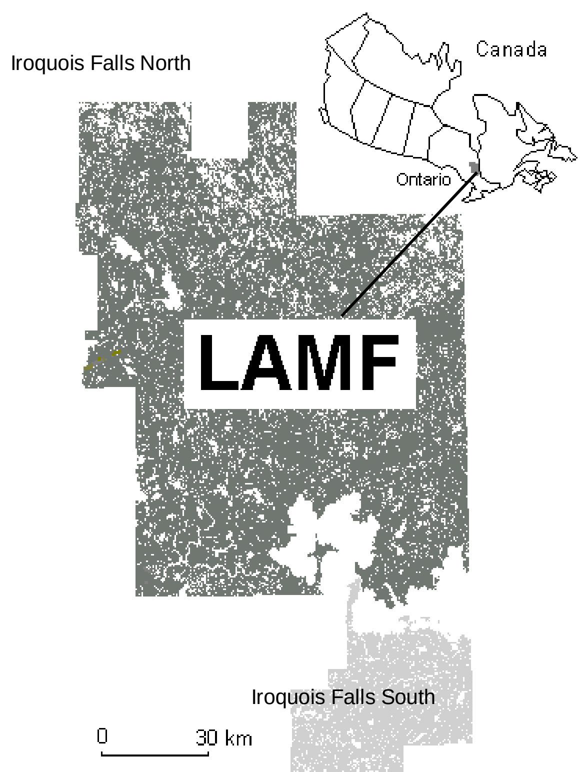

Figure 1. Location of the Lake Abitibi Model Forest (LAMF)

The physiography of the LAMF is dominated by the Great Northern Clay Belt (Griffin, 2001). This area near Baltic lowland is rolling and lower, and the elevation ranges from 250 to 350 m above sea level. A large area dominated by glacial outwash includes primarily fine texture clay, covered by organic deposits in poorly drained areas (Environment Canada, 2000 and Griffin, 2001). About 50% of the land in the LAMF is organic deposits or peatlands, and others are covered by glacial landforms such as eskers, moraines and drumlins. The climate of LAMF and its associated weather are due to the influence of 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 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 (*Cedrus*), larch (*Larix*), and balsam poplar (*Populus balsamifera*). Tree ages ranged from 2 to 283 in 2000, and were older in Iroquois Falls North than in Iroquois Falls South (see the regeneration year in Figure 7a for details). The vegetation and site data of the forest ecosystem are available in LAMF, and collected as the attribution data of GIS ArcView. To express each layer map processed in TRIPLEX1.0 and GIS, the simulation requires a data set 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 was operated in LAMF during the 1990s. The annual allowable cut (AAC) is approximately 750,000 m^3. This AAC was converted from the allowable harvest area (approximately 8,670 ha annually, 0.11% of the total forest area in LAMF land) as described in the Forest Management Plan which is renewable every five years. To ensure the areas that have been harvested were successfully regenerated, the regeneration activities are monitored based on the prescription that was developed for a specific harvest area. The regeneration success has increased significantly from 1985 to 2000 in the LAMF (Griffin, 2001). The observations of forest fire occurrence are 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 the 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 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). The average air temperature and precipitation are available at a spatial grid with a horizontal resolution of $3.75^{o} \times 3.71^{o}$ (longitude × latitude). Downscaling technique was applied for resolving the finer features of forest ecosystem that is sensitive to local climate and obtaining representative values at the centre points of each stand. We assumed values at centroid points represent averages of climate conditions in those stands. To downscale for 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 and reported by Oelschlagel (1995). For air temperature and precipitation, the monthly averages at every grid point were interpolated and the result was added to the averages in the target location. Figure 2 illustrates the annual temperature and precipitation downscaled for 1995 as an example.

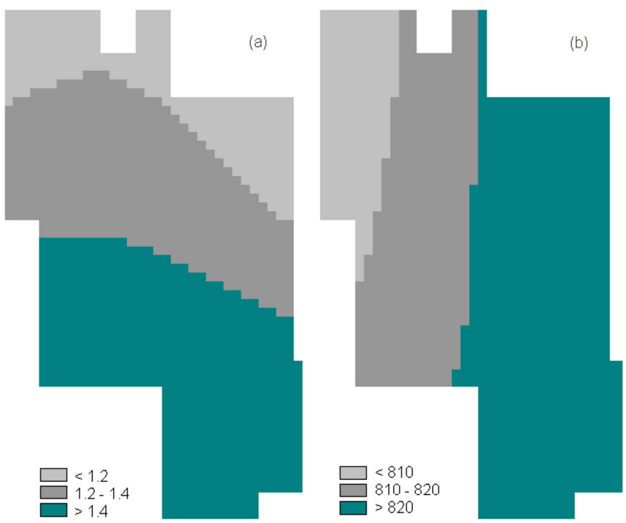

Figure 2. The annual temperature (C^{o})(a) and precipitation (mm)(b) downscaled for LAMF in 1995

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. One of its specialities is its integrity to simulate each monthly process of carbon cycle. The simulation of the TRIPLEX1.0 involves key processes and carbon dynamics 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 is summed up yearly. The structure of the TRIPLEX1.0 (Figure 3) includes four major components.

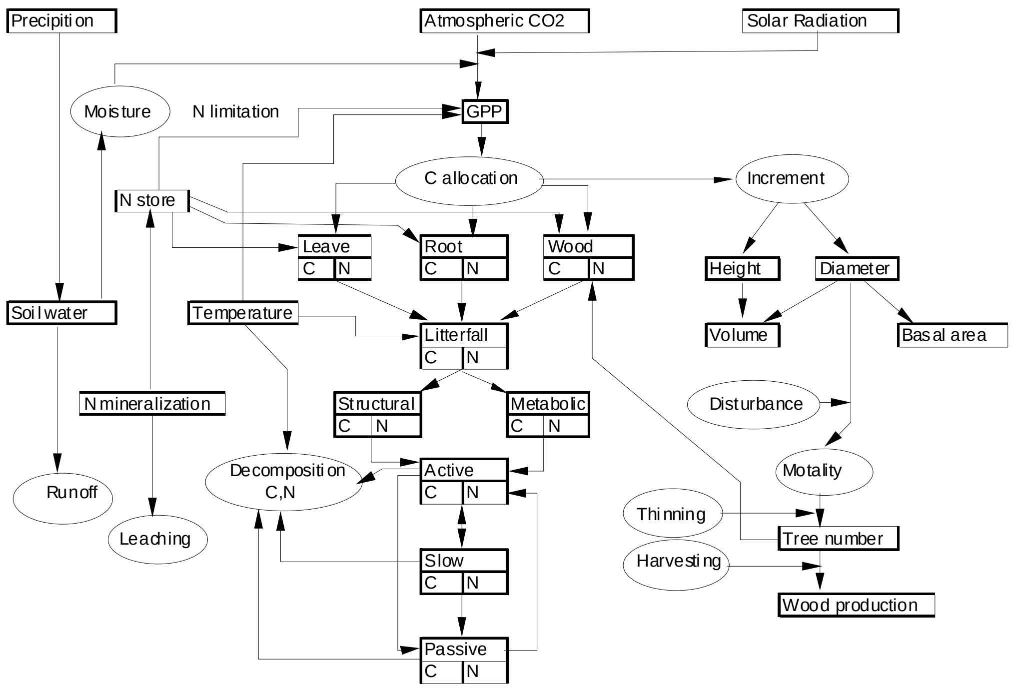

Figure 3. The structure of ecosystem simulation model TRIPLEX1.0 (Peng et al. 2002)

(1) Forest production. This sub-model estimates photosynthetically active radiation (PAR), Gross Primary Productivity (GPP), and above-ground and below-ground biomass. The PAR was calculated as a function of solar constant, radiation fraction, solar height, and atmospheric absorption. The initial PAR was estimated as a solar constant (1360 Wm^{-2}) (Bossel, 1996), and the solar radiation fraction was set as 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, vapour pressure deficiency, soil drought, and percentage of frost days in the month. There is a fixed fraction (C_{NPP}=0.39) suggested by Ryan et al. (1997) for estimating the proportion of NPP in GPP for boreal forest ecosystem. Carbon allocation was defined depending on the apportionment of carbon assimilation among the foliage, stem and root.

(2) 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). It 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.

(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 has been calibrated and validated for pure jack pine stand in Ontario (Peng et al., 2002; Liu et al., 2002c) and for major boreal tree species in central Canada (Zhou et al., 2003) before being applied to LAMF.

2.4. Simulations

The simulation was performed for net primary productivity (NPP), above-ground and below-ground biomass, soil carbon as well as forest growth. The ecosystem carbon balance for whole region was estimated based on simulation results. The carbon balance was calculated using the following equations:

Net Carbon Balance (NCB) = Carbon uptake (NPP) – Carbon Release

Net Biome Productivity (NBP) = NCB – Carbon Loss by Harvesting

where "Carbon Release" includes carbon emissions by root heterotrophic respiration and soil decomposition, NPP accumulates the forest biomass over years and produces litterfalls thatdecompose and add the carbon to soil, and the annual harvest is removing forest biomass away from the ecosystem and results in a decrease of carbon stock.

The parameters used in TRIPLEX1.0 for the boreal forest ecosystems in Canada are available from our previous study (Zhou et al., 2003). These parameters were adjusted depending on forest stand and site conditions. The primary parameters for this study is listed with their references in Table 1.

Table 1. Primary parameters used in the TRIPLEX simulations

Parameter	Description	Note
Tveg=5	Temperature of vegetation begin and end	a
Sla=6	Specific leaf area	b
Topt=15	Optimum temperature for producing GPP	b
Ccpp=0.39	Convert GPP to NPP	c
Cloud=0.4	Cloud ratio for a month	a
AlphaC=0.05	Canopy quantum efficiency	d
GamaS=0	Stem loss ratio	Assumption
Lnr=0.26	Lignin-nitrogen ratio from N Module	e
K1-K8	Max decomposition rate in soil	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)	e
AWL2=0.3	Relative root density (layer 2)	e
AWL3=0.2	Relative root density (layer 3)	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
AgeMax=200	Maxmum tree age to grow	Assumption
MiuNorm=0.07	Normal mortality ratio (yearly)	f
MiuCrowd=0.02	Crowding mortality ratio (yearly)	a
GamaR=0.21	Root loss ratio (yearly)	g
MaxGama=0.01	Max foliage loss ratio (yearly)	h

[a] Bossel, et al., 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] estimated based on literatures, and considered as <0.1 yearly when the tree density is less than 6000 trees ha^{-1} (Plonski, 1974; Mitchell, 2000); [g] Steele et al., 1997; [h] estimated based on results (0.069-0.083 yaer^{-1} in southern BOREAS area) of Gower et al., 1997.

3. Results and Discussions

3.1. Net Primary Productivity

The simulation results show the average NPP increased from 3.26 in 1990 to 3.34 (tC ha^{-1} yr^{-1}) in 2000. Comparing simulated NPP with other studies, the simulation of average (3.26 – 3.34 tC ha^{-1} yr^{-1}, SD=0.79) is consistent with the range estimated at stand level (2.16-3.92 tC ha^{-1} yr^{-1}, Gower et al., 1998) for NSA and SSA, and national level (3.08 tC ha^{-1} yr^{-1}, SD=1.15, data from Liu et al., 2002a) for LAMF (see Figure 5a and b). Our results are close to other studies for Ontario boreal forests, for example, using MIAMI model (Lieth, 1975) for LAMF in Ontario (3.54 tC ha^{-1} yr^{-1}, this study), CBM-CFS2 for Ontario's boreal area (3.65 tC ha^{-1} yr^{-1}, Liu et al., 2002a), and CENTURY4.0 for BOREAS of central Canada (2.54-2.73 tC ha^{-1} yr^{-1}, Peng et al., 1999). Our results indicate that the distribution of NPP for LAMF at landscape level was within the range estimated by Gower et al. (2.16-3.92 tC ha^{-1} yr^{-1}).

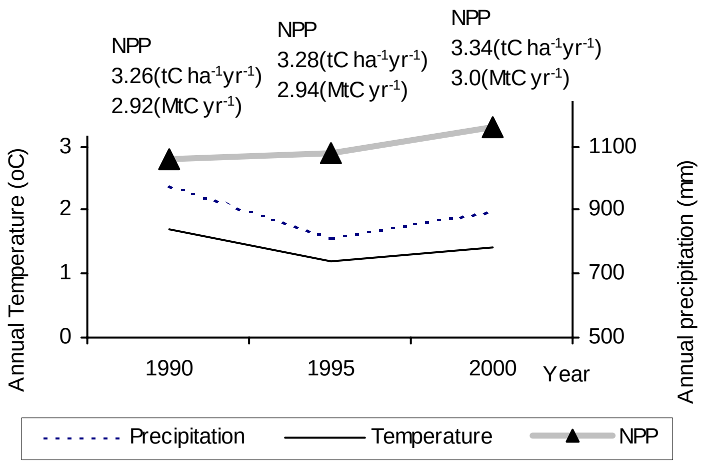

Figure 4. Variation of simulated NPP in relation to annual total precipitation and annual mean temperature in LAMF. The climate data are averaged over the study region.

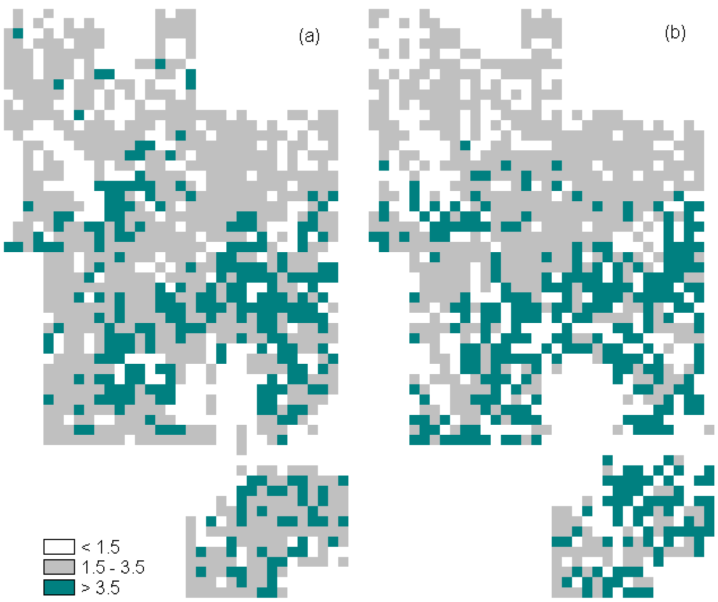

Figure 5. The comparison between NPP (t C ha-1 yr-1) simulations at landscape (a) and remote sensing (b) levels for LAMF in 1995. (a) was based on the simulation for 1995 (averaged 3.28 tC ha-1 yr-1, SD=0.79), and (b) was converted using spatial data from Liu et al. (2002a) for 1994 (averaged 3.08 tC ha-1 yr-1, SD=1.15). The grid size is 3x3 km.

The total NPP in LAMF also increased in the 1990s, but the increase rate varied with local climate conditions. The relationships between NPP and climate did not appear to be direct, however, our results show that the increase rate was affected by temperature and precipitation (Figure 4). For example, Figure 4 shows the different increases of annual NPP during the estimation period and corresponding climate conditions. Both mean annual precipitation and temperature were undulating from 1990 to 2000, and they were around 65 mm and 0.6^{o}C lower in 1995 than in 1990. The total annual NPPs were almost the same in 1990 and 1995. It can be considered that lower annual precipitation and temperature caused a lower rate of NPP increment in 1995. While the precipitation and temperature reascend in 2000, the annual NPP increased as well. Depending on the percentage of the variation, the annual temperature was more sensitive than precipitation to NPP.

3.2. Biomass

The results of average biomass density provided a range of 106.5-125.3 (t ha^{-1}) for the studied area of LAMF. In three primary major species, the biomass density of black spruce was 12% and 17% higher than aspen and jack pine in 2000 (see Table 2). The comparison between observation and estimation shows that the LAMF's above-ground biomass was occurring within the reasonable range: 75-100 t ha^{-1} obtained from Canada's forest biomass resources (Penner et al., 1997) for above-ground biomass in boreal forest ecosystems. Because black spruce had highest percentage (78%) of above-ground biomass in LAMF, the biomass density of black spruce represented approximately regional average at landscape level. It was 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 the difference exists among Boreal East (LAMF), West and Centre area. The understory biomass was not calculated independently because of its small proportion, e.g. less than one percent of total biomass (Gower et al., 1998).

Table 2. Comparison of simulated above-ground biomass[a] (t ha^{-1}) with estimations and observations at landscape level.

Black spruce	Trembling aspen	Jack pine	Reference [b]
95.2	84.9	80.8	Simulation using TRIPLEX1.0 in this study
91.1	80.8	73.3	1
	75-100 (all species)		2

[a] total biomass was estimated as 125.3, 111.8, and 106.5 tC ha^{-1} for black spruce, trembling aspen, and jack pine, respectively. [b] references: 1, Observations from the field data of BOREAS, central Canada including southern study area (SSA) and northern study area (NSA), Newcomer et al., 2000; 2, Estimated from the 1994 Canadian Forest Inventory, LAMF in Ontario, Penner et al., 1997.

The dynamics of below-ground biomass was also simulated for LAMF ecosystems. The below-ground biomass was calculated for coarse roots greater than 5 mm, and fine roots less than and equal to 5 mm (classified by Ryan et al., 1998). Generally speaking, a tendency for below-ground biomass is that different sites affected the proportion of above-ground and below-ground biomass. Roots are well-growing in poor soil, such as sandy, arid, or lower site class. Our simulation revealed the different percentages of below-ground to total biomass by site class (Figure 6). Averagely, the below-ground biomass was estimated as 24% of above-ground biomass in LAMF. This proportion is close to the results (regressed 23.2% and averaged 24.2%) reported by Kurz et al. (1996) and Ryan et al. (1997) for Canadian forest.

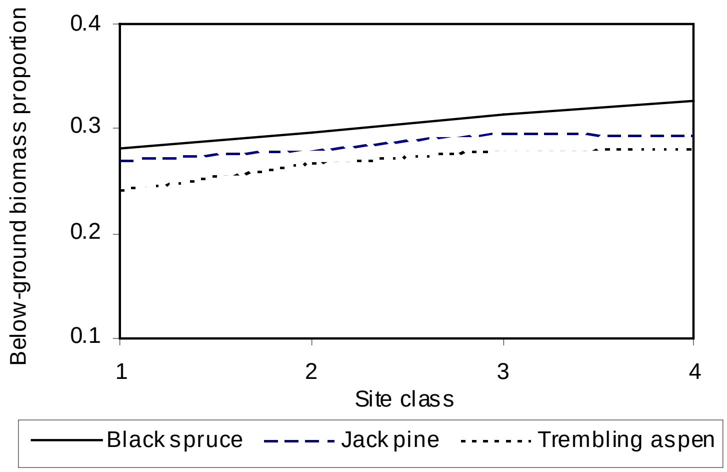

Figure 6. Simulated proportion of below-ground to above-ground biomass in LAMF for 2000, simulated using TRIPLEX1.0.

Table 3. Comparison of simulated soil carbon density (t C ha^{-1}) for LAMF in 2000 with measurements and estimations at landscape level

Average soil C density	Method	Reference [a]
Simulation:		
93.9(28.3) [b]	TRIPLEX1.0., LAMF, Boreal East	This study
72.7(20.3)	CENTURY4.0., Central Canada	1
125-130	CBM-CFS., Boreal East and West [c]	2
Measurement and estimation:		
121(45)	Soil C is to 100 cm depth, Boreal West	3
81(4.7)	Soil C is to 100 cm depth, Boreal West	4
111(5.6)	Soil C is to 100 cm depth, Boreal East	4
118(15.0)	Estimation, Boreal East and West	2
113.9(54.1)	Soil C is to 100 cm depth, Central Canada	5

[a] references: 1, Peng et al. 1998; 2, Kurz et al. 1992; 3, Johnston and Uhlig 1999; 4, Siltanen et al. 19975, 5, Halliwell and Apps 1997. [b] round brackets denote standard deviations of cited carbon values. [c] categorized for Ecoclimatic regions of Canada.

3.3 Soil carbon

Total soil carbon in LAMF is estimated at 83.7 MtC in 2000, and average soil carbon density is 93.9 tC ha^{-1} approximately (Table 3). All estimations of soil carbon in this study are limited for forest lands only, which do not include lakes, rivers, and any non-forest lands. The contribution of soil carbon to total ecosystem carbon, which includes above-ground biomass, below-ground biomass, detritus, and soil carbon, was estimated and compared with two age class groups. Results indicated that an average soil carbon contributes approximately 60% of total ecosystem carbon for all age stands. Younger stands (<100 years) had higher percentage (around 66%) and older stands (>100 years) got lower (around 51%) in LAMF. This was because biomass carbon occurred less in younger stands than older. The total forest ecosystem carbon (including vegetation, detritus, and soil) content was 154.4 tC ha^{-1} with 60% of the carbon (93.9 tC ha^{-1}) in soil including litterfalls. This means that the proportion of soil and above-ground biomass carbon is in agreement with our analysis of the field data (the ratio is about 2:1) 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 Price et al. (1997) and Peng et al. (1998) in their studies for boreal ecosystems in central Canada. Unfortunately, we don’t have the point by point of field measurements of soil carbon for entire LAMF, so we have to use the existing national soil carbon database as general reference to verify our model simulations. As references for an overview, Table 3 compares the soil carbon density with other recent studies for Canada’s boreal region. The soil carbon density ranges from 81 to 113.9 tC ha^{-1} for field measurements and 72.7 to 118 tC ha^{-1} for model simulations. Our TRIPLEX simulation has a good agreement within the ranges of observations.

Generally, litterfalls return carbon from biomass carbon stocks to soils, and different stand age and tree species determine the soil carbon flux. Based on our simulation, we noticed little differences in soil carbon between the stands with different tree species; however, we did not compare them with observations in this study because of lacking necessary data on soil details such as soil nutrient, layer depth, and moisture. We also found no significant variation of soil carbon in LAMF during the period from 1990 to 2000, although climate condition was changing. It implies that soil carbon was relatively stable in LAMF without intensive disturbances (e.g., neither large harvest cutting nor forest fire) which can cause the increase of soil carbon flux and result in a variation of soil carbon.

3.4 Spatial distribution of carbon

The distribution of biomass density was closely related with tree age distribution (see Figure 7). The soil type, stand nutrition condition, and site class also determine the accumulation rate of biomass. We divided the LAMF region into two sub-regions (Iroquois Falls North and South) and investigated their differences in spatial distribution of carbon.

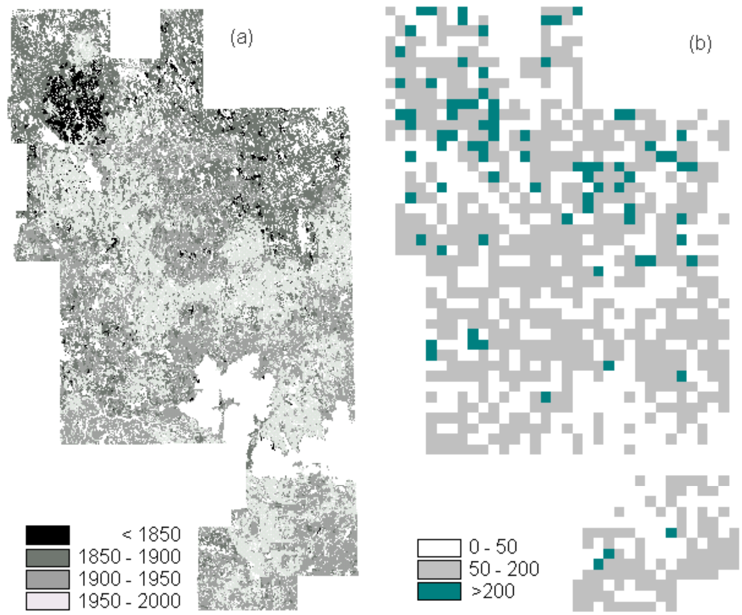

Figure 7. The distributions of the regeneration year (a), and total biomass density (t ha-1) including above- and below-ground (b) for LAMF in 2000. The regeneration year was inventoried at stand level and biomass was estimated at landscape level (grid size is 3x3 km).

Table 4 shows how these factors affected NPP and biomass density in different regions of LAMF, and Figure 5a and Figure 7b illustrate spatial distributions of NPP and biomass density at landscape level. Patterns for each stand are summed (Table 4) to provide an assessment of the biomass accumulation and productivity. We found that younger stands had higher NPP and lower biomass density; poor sites (site class 3 and 4) had both lower NPP and biomass density; trembling aspen stands generally had higher NPP; and both NPP and biomass density were slightly higher in Iroquois Falls North than South (Table 4, Figures 6 and 7). As shown in Figure 5 and Figure 7a, the comparison with the simulation at broad scale (Liu et al., 2002a) imply the higher NPP occurred in younger stands, having regeneration in the years after 1950.

3.5. 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 5). Figure 8 illustrates the carbon budget of LAMF for 2000. The net carbon balance 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. Above-ground biomass was about 76% of total biomass carbon. The carbon content of harvesting was converted from local data of LAMF using average wood carbon density, which was reported by Zhou et al. (2003) as 0.22 tC m-3 (0.19, 0.23 and 0.22 for trembling aspen, black spruce, and jack pine, separately).

Table 4. Estimation of carbon spatial distribution in landscape level for boreal forest of LAMF in northeast Ontario.

		Average stand age (years)		
Site class	Species [a]	0-50	50-100	100-
NPP (t C ha^{-1} yr^{-1}):				
1	SB	> 3.0	> 3.0	>3.0
	PJ	> 3.0	> 3.0	>3.0
	AT	> 3.0	> 3.0	>3.0
2	SB	> 3.0	> 3.0	1.5-3.0
	PJ	> 3.0	> 3.0	1.5-3.0
	AT	> 3.0	> 3.0	1.5-3.0
3	SB	1.5-3.0	1.5-3.0	1.5-3.0[b]
	PJ	1.5-3.0	1.5-3.0	1.5-3.0[b]
	AT	1.5-3.0	1.5-3.0	1.5-3.0
4	SB	1.5-3.0	< 1.5	< 1.5
	PJ	1.5-3.0	< 1.5	< 1.5
	AT	1.5-3.0	< 1.5[c]	< 1.5
Biomass (t C ha^{-1}):				
1	SB	<50	50-200	>200
	PJ	<50	50-200	>200
	AT	<50	50-200	>200
2	SB	<50	50-200	>200[d]
	PJ	<50	50-200	>200[d]
	AT	<50	50-200	50-200
3	SB	<50	<50	50-200
	PJ	<50	<50	50-200[e]
	AT	<50	<50	50-200[e]
4	SB	<50	<50	<50
	PJ	<50	<50	<50
	AT	<50	<50	<50

[a] SB, PJ, and AT refer to black spruce, jack pine, and trembling aspen respectively. [b] lower (<1.5) in Iroquois falls South. [c] higher (1.5-3.0) in Iroquois falls North. [d] lower (50-200) in Iroquois falls South. [e] lower (<50) in Iroquois falls South..

Table 5. The dynamics of carbon stocks and balance in LAMF's forest ecosystem

Variable	1990	1995	2000	Average
Total C stock (Mt C)	132.4	135.8	139.2	135.8
Biomass C stock (Mt C)	48.3	52.0	55.5	51.9
Litter and soil C stock (Mt C)	84.1	83.8	83.7	83.9
C uptake (total NPP) (Mt C yr^{-1})	2.92	2.94	3.0	2.96
Harvesting (Mt C yr^{-1})	0.13	0.14	0.12	0.13
C release (Mt C yr^{-1})	0.94	0.95	0.96	0.95
Net C balance (Mt C yr^{-1})	1.98	1.99	2.04	2.01

In Figure 8, biomass and soil carbon stocks were estimated before harvesting. However, harvested carbon contents did not affect net carbon balance significantly because there is a limit of allowable harvest in LAMF from 1990 to 2015. The actual total harvested volume has been lower than the allowable level from 1990 to 2000 (approximately 6,200 ha annually, 0.08% of total LAMF forest land). Unfortunately, we did not take into account the effect of forest fire on carbon balance in this study. Actually, the forest fires did not occur frequently in LAMF during the 1990-2000. For example, the total burns covered only 0.38% of the area of LAMF in the 1990s. This implies that carbon released from the ecosystem by forest fires was very limited to impact the carbon balance of LAMF ecosystem. Also, the current formation of the TRIPLEX model does not include the fire simulation module that will be incorporated in the new version of TRIPLEX.

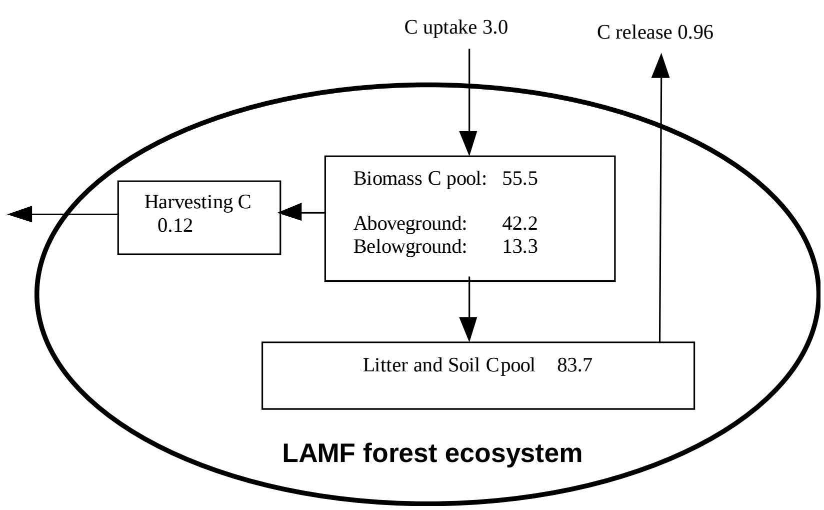

Figure 8. The carbon budget of LAMF forest ecosystem in 2000. Net carbon balance (NCB) and net biome productivity (NBP) were 2.0 Mt C and 1.9 Mt C yr^{-1}, respectively.

The simulation shows that the LAMF forest ecosystem was acting as a carbon sink in the 1990s (NCB was around 2 Mt C from 1990 to 2000), although there was a large carbon source in Ontario's forest ecosystems (-31 Mt C estimated in 1990) as reported by Peng et al. (2000). The reasons can be considered as most of younger stands (average stand age was 72 years) in LAMF had higher productivity, and very few disturbances (e.g. harvesting and forest fire) occurred in LAMF in the 1990s.

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 forest land 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 LAMF of north Ontario was estimated between observed values of NSA and SSA in central Canada. However, the NPP was sensitive to climate conditions and obviously affected by lower annual temperature and precipitation in 1995, although temporal dynamics of biomass and NPP were increasing in LAMF in the 1990s. As an integrated temporal and spatial simulation, an estimation of carbon distribution was provided based on the stand features (tree age, species, soil type, and site class) at landscape level. This study suggests an estimation method and provides integrated information for local forest managers to develop ecological and carbon-based indicators. Our results show that the LAMF forest ecosystem was acting as a carbon sink in the 1990s, and in opposition to the large carbon source in Ontario's forest ecosystems reported previously by Peng et al. (2000) and Liu et al. (2002b). That is because younger stands and few disturbances occurred in LAMF. As a dynamic simulation, we feel that the future improvement should be enhanced, especially on effects of future climate change and impacts of ecosystem disturbances that will be incorporated in the new version of TRIPLEX1.0. In addition, since the TRIPLEX1.0 operates on a monthly time step, the simulation for daily carbon flux and balance is limited and would be improved through ongoing projects and Fluxnet-Canada network.

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