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Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation

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Abstract

The effects of different harvesting intensities and rotation lengths on the long-term carbon (C) and nitrogen (N) dynamics of boreal forests in central Canada were simulated using the process-based ecosystem model CENTURY 4.0. Three harvesting intensities and four rotation lengths were investigated. Results suggest that intensive harvesting regimes (e.g. whole-tree harvesting (WTH)) would decrease total ecosystem C, soil C storage, and N availability, compared with conventional harvesting (CH). Harvested biomass would increase with increasing harvesting intensity. Net loss of forest productivity (indicated by above-ground biomass) would be higher in higher productivity stands in the low boreal ecoclimatic region. For a given harvesting intensity, total ecosystem C stock and N availability would be highest with long rotations (120 years) and reduced under shorter rotations (60 and 30 year). Extremely short rotations (i.e. 30 year) would reduce boreal forest productivity by as much as 65%. Longer rotations and less intensive harvesting could increase C sequestration about 36–40% in the boreal forest region of central Canada. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Carbon sequestration; Ecosystem model; Biomass; Soil carbon and nitrogen; Rotation length

1. Introduction

There is growing interest in understanding the influence that disturbances exert on regional ecological patterns and processes in relation to natural resource management. In many forests, timber harvesting competes with other natural disturbances (e.g. wildfire, wind, insects, disease) as the major agent of ecosystem disturbance. Concerns have been expressed about the effects of intensive timber harvesting on the sustainability of forest ecosystems (Kimmins, 1977; Dyck and Cole, 1994; Wei et al., 1997; Morris et al., 1997; Jurgensen et al., 1997). Intensive forest management practices based on short rotations and high levels of biomass utilization (e.g. whole-tree harvesting (WTH)) may significantly reduce forest site productivity, soil organic matter (SOM), and

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nutrient availability on some sites. Boyle et al. (1973), Freedman (1981) provide overviews of the effects of intensive timber harvesting on nutrient budgets. Based on data from a variety of studies, Johnson (1992) summarized the potential effects of harvesting, site preparation, and fertilizer treatments on soil carbon (C). Keenan and Kimmins (1993) reviewed, from a broad perspective, the ecological effects of clear-cutting. The effects of timber harvesting on site productivity, SOM, and nitrogen (N) availability in inland northwest forests were also discussed recently by Jurgensen et al. (1997).

A number of studies indicate that nutrient availability and SOM consistently decrease for 10–50 years after harvesting, but return to near pre-felling values by 60–90 years (Boyle, 1976; Covington, 1981; Gordon, 1983; Hendrickson et al., 1987; Johnson, 1992; Olsson et al., 1996). Unfortunately, few empirical studies have examined the effect of harvesting regimes on C and N dynamics of boreal forests in central Canada, although some studies have reported on the removal of soil organic C and total C after forest harvesting (Morrison et al., 1993; Pennock and van Kessel, 1997). Data on long-term post harvest ecosystem responses (> 100 years) are not available in the literature. Experimental methods of estimating the long-term (e.g. 100–600 years) effects of harvesting will not provide information in a timely manner. Process-based ecosystem models may provide an alternative approach to understanding the effects of harvesting regimes on C and N dynamics of forest ecosystems (Aber et al., 1978, 1982; Bengtsson and Wiström, 1993; Morris et al., 1997; Roff and Ågren, 1999).

Boreal forest ecosystems represent important pools in the global C cycle and act as C sinks and sources of atmospheric C (Apps et al., 1993; Dixon et al., 1994). Increasing interest in global C budgets have resulted in greater research efforts to understand and quantify the role of the boreal forest ecosystems (e.g. Apps and Price, 1996). A previous study (Peng et al., 1998; Peng and Apps, 1999) demonstrated the ability of the process-based plant-soil model CENTURY 4.0 to simulate net primary productivity (NPP), biomass and soil C in Canadian boreal forests under current climate conditions. The sensitivity of C dynamics in Canadian boreal forests to future possible climatic change and fire disturbance regimes also have been examined (Peng and Apps, 1998; Price et al., 1999; Apps et al., 2000; Jiang et al., 1999). Here, we extend these studies and report on the long-term effects of harvesting intensities and rotation on C storage in vegetation and soil, and on N dynamics in the Boreal Forest Transect Case Study (BFTCS) area of central Canada. Two specific hypotheses are tested. First, does intensive harvesting reduce ecosystem C stock and N availability? Second, does extremely short harvesting rotation result in a net loss of forest productivity, ecosystem C sequestration?

2. Methods

2.1. Study area

The BFTCS (Price and Apps, 1995) extends over a distance of 1000 km and is oriented approximately southwest–northeast along a pronounced ecoclimatic gradient across the boreal forests of Saskatchewan and Manitoba (Fig. 1). It was selected for this study for a number of reasons.

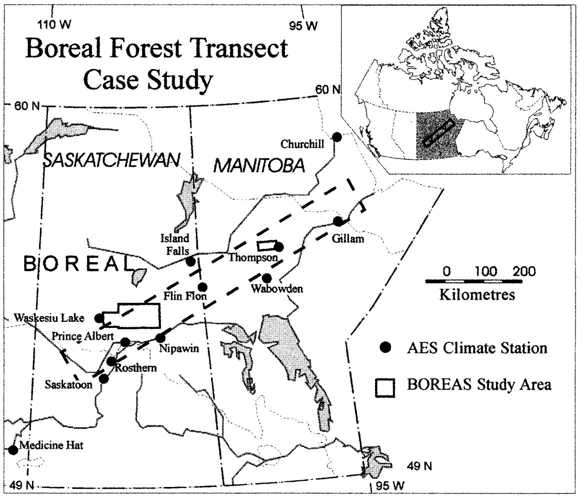

Fig. 1. Map of Saskatchewan and Manitoba showing the locations of the BFTCS and BOREAS study areas, and the climate stations used in the simulations (Adapted from Price and Apps (1995)).

First, the BFTCS is one of the Global Change and Terrestrial Ecosystems (GCTE), a core project of the International Geosphere Biosphere Program (IGBP) high latitude transects (Koch et al., 1995). Second, detailed vegetation and soil databases are available across the BFTCS (Halliwell et al., 1995; Halliwell and Apps, 1997a,b,c) against which to test the model's ability to predict aboveground biomass and soil C for different climatic conditions and soil types within the boreal biome. Third, there is a pronounced gradient of land-use and land-use intensity across the transect, ranging from modern forestry practices in the south (Prince Albert Model Forest) to traditional native land practices in the north (Linklater, 1995).

The characteristics of the selected boreal forest ecoclimatic regions in central Canada are described below in Table 1. Vegetation at the Thompson site is characterized by forests of black spruce (*Picea mariana* (Mill.)) and jack pine (*Pinus banksiana* Lamb.), as well as some paper birch (*Betula papyrifera* Marsh.), with understories of feathermoss, bog cranberry, blueberry (*Vaccinium* spp.), Labrador tea (*Ledum groenlandicum*), and lichen (*Cladina* spp.). Summers are cool and short, about 5 months long, while winters are very cold with persistent snow cover. Annual precipitation is moderate, between 300 and 500 mm. In the Prince Albert region, deciduous forests composed of trembling aspen (*Populus tremuloides* Michx.), with secondary quantities of balsam poplar (*P. balsamifera L.*), and understories of mixed herbs and shrubs dominate sites. White spruce (*P. glauca* Voss) and balsam fir (*Abies Balsamea* (L.)) are the climax species in this region, but are not well represented due to the frequent occurrence of fire and past logging practices. Most sites have Gray luvisols soil (Agriculture Canada Expert Committee on Soil Survey, 1987). Open stands of jack pine occur on dry sites, with Eutric and Dystric Brunisol soils. Black spruce is an important edaphic climax species in the wetlands. Summers are warm, with maximum precipitation occurring during July. Winters are cold and snowy.

Table 1
Site parameters for two selected boreal forest locations in central Canada

	Low boreal (Prince Albert)	High boreal (Thompson)
Latitude (°)	53.37N	57.17N
Longitude (°)	105.08W	97.50W
Mean monthly maximum temperature (°C)	24.45 (July)	22.52 (July)
Mean monthly minimum temperature (°C)	−25.25 (January)	−30.76 (January)
Annual precipitation (mm)	398	544
Dominant vegetation[a]	PICO+PIGL	PIGL+PIMA
Soil type[b]	E.EB	H.FB
Soil texture		
Clay (%)	13	33
Silt (%)	14	29
Sand (%)	73	38

[a] Vegetation name acronyms follow the flora of Canada (Scoggan, 1979): PIMA (*P. mariana*); PICO (*P. contorta* Dougl); PIGL (*P. glauca*).

[b] Soil classifications (subgroup) are from the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987). E.EB, Eluviated Eutric Brunisol; H.FB, Humo-Ferric Podzol.

2.2. CENTURY4.0 model

CENTURY, developed by Parton et al. (1987, 1993), is a semi-mechanistic process-based model of plant-soil ecosystems that simulates the dynamics of C and N of various plant-soil systems including grassland, agricultural land, savannas and forests. Since it incorporates representations of key processes relating to C assimilation, turnover and decomposition, the model can be used to simulate many management measures, including harvesting, fertilization, and wildfire control. The model has been previously described in detail by Parton et al. (1987, 1993), Metherell et al. (1993). CENTURY 4.0 (the forest version of CENTURY) has three major submodels: (1) a biophysical submodel that calculates hydrological and thermal driving variables; (2) a forest production submodel that simulates above- and below-ground vegetation processes; and (3) a SOM submodel that calculates dynamic C and N flows in soil and litter pools.

The forest production submodel partitions tree biomass into several compartments: foliage, fine and coarse roots, fine branches, and large wood. C and N are allocated to different plant parts using a fixed allocation scheme although allocation coefficients may be used for young and mature stands. The soil submodel consists of eight organic matter pools. Four represent surface and root litter, and the other four represent SOM. The SOM pools include two "active" fractions that have rapid turnover times (1–5 years) representing microbial biomass and metabolites divided into a surface and a soil pool; a 'slow' fraction with intermediate turnover time (20–40 years) that represents stabilized decomposition products; and a 'passive' fraction with slow turnover time (200–1500 years) that represents highly stabilized organic matter. C flows between these pools are controlled by decomposition rate and microbial respiration parameters, both of which are expressed as functions of soil texture. The turnover times of all pools vary with a soil abiotic decomposition parameter and are calculated as a function of monthly temperature and precipitation.

2.3. Model validation

Two methods have been used to validate the CENTURY model (Parton et al., 1993; Peng et al., 1998; Bolker et al., 1998). The first method used a linear regression of the observed data against the simulation model results; the second checked the model estimates against predictions from other well-established models such as empirical regression models. CENTURY 4.0 has been validated for the BFTC in central Canada using field data of aboveground biomass and SOM (Peng et al., 1998). The results indicate that CENTURY 4.0 gave soil C accumulation estimates at the transect scale that were consistent with established empirical regression model estimates and were highly correlated with observed values ($R^2 = 0.92$). CENTURY 4.0 also simulates both aboveground biomass and net N mineralization reasonably well across the range of present climatic conditions represented in the transect. Additional testing of the ability of CENTURY 4.0 for simulating NPP has been recently reported by Peng and Apps (1999), in which the simulated mean NPP by CENTURY 4.0 lied within the range of observed data of Gower et al. (1998). In addition, the study by Price et al. (1999) further demonstrated that CENTURY 4.0 was able to reproduce spatial variation of soil and litter C densities satisfactorily and showed good agreement of ecosystem carbon with both local field data and the simulations of the forest succession model of FORSKA2 (Prentice et al., 1993) across the BFTC under current climate conditions. We believe these previous work performed in this regions provides a scientific foundation and the reliability of model for further investigation of long-term effects of forest management regimes on C and N dynamics in Canadian boreal forests.

2.4. Model parameterization and simulation scenarios

The main parameters for initial values of productivity, above-ground biomass, decomposition, and soil C have been previously described in detail by Peng et al. (1998). Only values pertinent to the present study are discussed here.

The major input variables for the model include: monthly mean maximum and minimum air temperature, monthly precipitation, soil texture, atmospheric and soil N inputs, plant lignin content, and initial soil C and nutrient levels. Non site-specific parameters for boreal forests used in other studies (Metherell et al., 1993; Peng et al., 1998) were left unchanged. Site-specific parameters and initial conditions, such as soil texture (clay, silt and sandy content) (Table 1), bulk density, soil pH, soil C content for the 0–20 cm layer, and drainage characteristics of soil were obtained from field data (Siltanen et al., 1997). Some site-specific parameters for boreal forest ecosystems were unavailable, requiring modification of existing values for temperate coniferous forests—a parameterization procedure discussed in greater detail in Peng et al. (1998). These parameters include: maximum gross and net forest production, optimum and maximum temperature for production, and a scaling factor for potential evapotranspiration (PET). CENTURY 4.0 also requires estimations of N fluxes in ecosystem. Atmospheric N deposition and fixation input, which were not available from the literature, were estimated using a simple linear function of precipitation based on observed data (Metherell et al., 1993).

For each site, CENTURY 4.0 simulations were run for 5000 years to reach equilibrium under natural conditions using repeated mean monthly temperature and CENTURY's stochastic precipitation generator. Monthly mean maximum and minimum temperature and precipitation values were calculated by CENTURY 4.0 using the 30-year normals (1950–1980) for Atmospheric Environment Service (AES, 1983) climate stations. For this run-up period, a random fire disturbance regime (with an average interval of 100 years over the 5000-year run-up) was used to represent natural disturbance regimes. To minimize artifacts associated with the initial conditions (end of the 5000-year run-up), each of the scenarios discussed below were then run for a further 300–500 years, and the analyses performed on simulation results of the last 300–500 years.

Harvesting regimes affect C and N dynamics in different ways, depending upon the harvesting intensity and rotation length. Following the study of Bengtsson and Wiström (1993), C and N dynamics are simulated and compared under the following harvesting intensities and rotation lengths:

- conventional harvesting (CH): 100% removal of stems from site, branches and needles left on site;
- Whole-tree harvesting (WTH): 100% stem utilization plus 90% removal of branches and needles, the rest of the branches and needles remain on site;
- complete-tree harvesting (CTH): 100% removal of stem, branches and needles plus 90% roots extracted from site;
- no harvesting disturbance (NHD): no stem, branches, needles or roots removed from site.
- Rotation lengths of 30, 60, 90, and 120 years were combined with both CH and intensive harvesting (i.e. WTH) to examine the sensitivity of C and N dynamics to different harvesting regimes.

To investigate the effects of harvesting on biomass and soil organic C, CENTURY 4.0 requires parameters that specify the fractions of live leaves, live fine branches, live large wood, and fine and coarse roots removed from pools by the harvesting (Metherell et al., 1993). In addition, the fraction of nutrients that are returned to the soil in inorganic forms from each biomass component that is removed by the harvesting event must be specified. The parameters used in the present study (Table 2) were derived from the studies of Bengtsson and Wiström (1993), Morrison et al. (1993).

3. Results

3.1. Effects of different harvesting intensities

Table 3 summarizes the simulated effects of three different harvesting regimes on two sites (Prince Albert and Thompson) along the BFTCS, as expressed on the basis of a 100-year management program. Differences in above-ground biomass and soil C between CH and WTH are substantial for both Prince Albert and Thompson.

Table 2
Parameters for three harvesting intensities used in CENTURY 4.0 simulations

Specific parameters	CH	WTH	CTH	NHD
Percentage (%) of tree biomass removed from pools				
Live leaves	0	90	100	0
Live fine branches	0	90	100	0
Live large wood	100	100	100	0
Percentage (%) of live root components that die				
Fine root	90	90	90	0
Coarse root	70	70	90	0
Percentage (%) of carbon in harvested material that is returned to the ecosystem				
Live leaves	100	10	0	100
Fine branches	100	10	0	100
Large wood	0	0	0	100
Percentage (%) of nitrogen in harvested material that is returned to the ecosystem				
Live leaves	100	10	0	100
Fine branches	100	10	0	100
Large wood	0	0	0	100

The parameters values are derived form Bengtsson and Wiström (1993), Morrison et al. (1993).

Table 3
Standing stock of C and N in biomass, soil and ecosystem as a whole, plus N mineralization and availability in related to harvesting intensity of 100 year rotation

Location	Harvesting intensities	AG-Biomass (Mg C ha^{-1})	Soil-C (Mg ha^{-1})	Ecosystem-C (Mg ha^{-1})	Net N	Removal N (g m^{-2} year^{-1})
Prince Albert (PA)	CH	25.17	27.79	89.50	2.38	15.18
	WTH	14.72	19.09	52.98	1.44	16.16
	NHD	172.18	41.72	304.41	3.61	24.49
Thompson (TH)	CH	48.77	73.20	199.40	2.83	19.81
	WTH	29.04	48.89	116.44	1.82	21.63
	NHD	175.48	70.88	362.18	3.35	22.36

Values are an average for a 500-year simulation. AG-Biomass, Soil-C, Net N, removal N, Ecosystem-C refer to above-ground biomass, total soil carbon, net N mineralization, removal nitrogen, and total ecosystem carbon, respectively. CH: conventional harvesting; WTH: whole-tree harvesting; NHD: no harvesting disturbance.

Nitrogen availability also shows a distinct difference between the two harvesting regimes.

On the low boreal ecoclimatic site (Prince Albert), above-ground biomass, averaged over the 500-year period, are 25.2 Mg C ha^{-1} under CH regime and 14.7 Mg C ha^{-1} under WTH. The mean values of soil C are 27.8 and 19.1 Mg C ha^{-1} for CH and WTH, respectively. Nitrogen availability for WTH is about 40% less than for CH. Total ecosystem C storage decreases by about 41% when CH is replaced by WTH.

On the high boreal ecoclimatic site (Thompson), above-ground biomass and soil C, averaged over the 500-year period for CH regime are 1.5–1.7 times higher than the WTH. Nitrogen availability for WTH is about 36% less than under CH regime. The net loss of N availability for Thompson is about 4% less than in low boreal ecoclimatic region (Prince Albert). Total ecosystem C storage for WTH is about 42% less than for CH, which is similar to the reduction in Prince Albert.

3.2. Effects of rotation lengths

Table 4 shows the predicted effects of different rotation lengths for CTH on above-ground biomass, soil C, net N mineralization and ecosystem C. The mean values of above-ground biomass for rotation lengths of 30, 60, 90, 120 years range from 7.7 to 27.4 Mg C ha^{-1} for Prince Albert, and from 14.1 to 58.8 for Thompson, respectively (Table 4). In general, soil C increased with rotation length in both low and high boreal ecoclimatic regions. N availabilities show similar variation with soil C but the difference is less pronounced. The estimated total ecosystem C ranges from 57.2 to 97.5 Mg ha^{-1} in Prince Albert and from 108.4 to 208.1 in Thompson, respectively. Increased rotation length yielded higher total ecosystem C storage at both sites. Total ecosystem C storage for short rotations (30 years) was reduced by about 36% at Prince Albert and 40% at Thompson, compared with a standard 90-year rotation. The temporal dynamics of above-ground biomass and soil C are strongly regulated by rotation length, and C stocks start to decrease at the end of 900 year with a shift from 90 to 30-year rotation at both Prince Albert and Thomson (Fig. 2). However, the decrease of C stocks is less pronounced in soil than above-ground biomass.

3.3. Interactive effects of harvesting intensities and rotation lengths

The interactive effects of harvesting intensities and rotation lengths have been investigated using a combination of the increase of rotation length and harvesting intensity (Table 5). As expected, total ecosystem C would increase with an increase of rotation length for a given harvesting intensity scenario. Total estimated ecosystem C reached maximum values ranging from 176 to 213 Mg C ha^{-1} for two sites under an elongated (120-year) rotation with less intensive harvesting (CH).

Table 4
Standing stock of C and N in biomass, soil and ecosystem as a whole, plus N mineralization and availability under CTH regime with four different rotation lengths

Location	Rotation length (year)	AG-Biomass (Mg C ha^{-1})	Soil-C (Mg ha^{-1})	Ecosystem-C (Mg ha^{-1})	Net N (g m^{-2} year^{-1})	Removal N (g m^{-2} year^{-1})
Prince Albert (PA)	30	7.65	22.68	57.19	2.12	15.26
	60	15.27	26.22	74.74	2.55	15.24
	90	22.23	28.30	88.67	2.69	15.16
	120	27.42	29.23	97.54	2.80	15.12
Thompson (TH)	30	14.08	51.03	108.41	2.60	15.02
	60	28.77	59.52	144.31	2.71	14.85
	90	44.87	67.30	182.02	2.86	14.70
	120	58.83	71.13	208.08	2.93	14.61

Values are an average for a 300-year simulation. AG-Biomass, Soil-C, Net N, removal N, Ecosystem-C refer to above-ground biomass, total soil carbon, net N mineralization, nitrogen removal, and total ecosystem carbon, respectively.

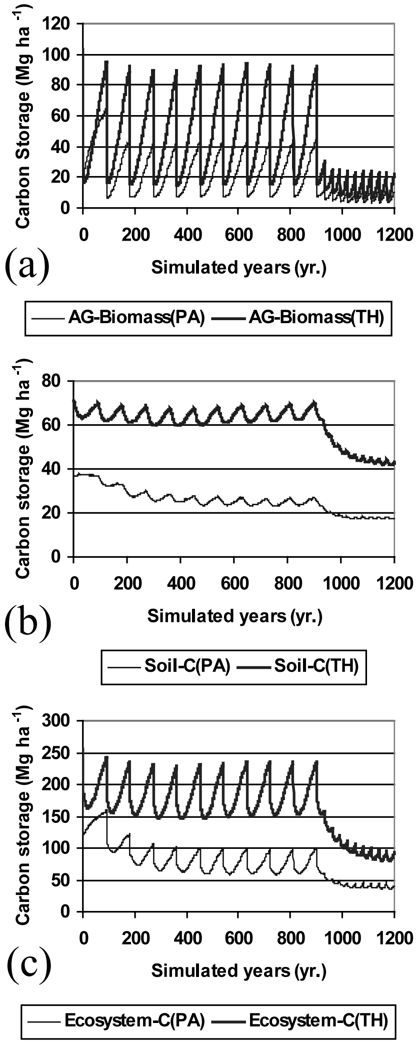

Fig. 2. Simulation of temporal dynamics of (a) above-ground biomass (AG-Biomass), (b) soil carbon (Soil-C) and (c) total ecosystem carbon (Ecosystem-C) using ten consecutive rotations of 90 years followed by ten of 30 years each with WTH. PA and TH refer to Prince Albert and Thompson, respectively.

Lower values of ecosystem C, ranging from 50 to 82 Mg C ha^{-1}, were associated with a combination of a short (30-year) rotation with intensive harvesting (WTH). Although the variation of above-ground biomass and soil C under different interactive effects showed similar trends, loss of C from above-ground biomass was about three to four times higher than that from soil.

The results also indicated that removal of N decreased with longer rotations and low tree utilization. However, the variation of N availability did not follow the trends of removal of N. In general, simulated net N mineralization under longer rotation and less intensive harvesting was about one to 2.5 time higher than that under shorter rotation with intensive harvesting regimes. For a given harvesting intensity, the difference in net N mineralization among four rotation length scenarios (Table 5) was minor. This minor difference may be because shorter rotations accelerate N cycling which may partially compensate N availability caused by N removal from the site.

4. Discussion

CENTURY is one of the most established ecosystem process models. Although the regression-based forest production submodel described in CENTURY is relatively simple, the robust SOM submodel of CENTURY has been used frequently by researchers (Peng et al., 1998; Peng and Apps, 1998; Price et al., 1999; Mikhailova et al., 2000) and fully or partly incorporated into other ecosystem models (Comins and McMurtrie, 1993; Friend et al., 1997, Kirschbaum, 1999, Chen et al., 2000; Peng et al., 2002). Recently, Jiang et al. (2002) used the CENTURY 4.0 to investigate the influence of different harvest disturbance regimes (e.g. CH, whole tree harvesting, no biomass removal) on the carbon stocks and fluxes of Chinese boreal forest ecosystems. The simulated results suggested that intensive whole tree harvesting (with a 100-year rotation) would result in a reduction of 81% in biomass and of 49% in litter, relative to a no-harvest reference. Soil carbon showed the same decreasing trend as biomass with increasing harvesting intensity and decreasing rotation length.

A number of studies have investigated effects of harvesting regimes on C storage in individual stands (Dewar, 1990, 1991; Harmon et al., 1990) and at the landscape-level (Price et al., 1997; Kurz et al., 1998); or the role of rotation lengths and growth rates on C storage (Cooper, 1983; Marland and Marland, 1992). Harmon et al. (1990) suggested that conversion of old-growth forest to

Table 5
Interactive effects of harvesting intensities and rotation lengths on C and N dynamics of boreal forests

Harvesting Intensities		Prince Albert (PA)				Thompson (TH)			
		Rotation Lengths (years)				Rotation Lengths (years)			
		30	60	90	120	30	60	90	120
CH	AG-Biomass (Mg C ha^{-1})	15.06	36.32	53.13	68.78	12.85	32.31	47.90	71.18
	Soil-C (Mg ha^{-1})	30.65	37.46	40.54	42.65	54.75	64.63	68.79	62.23
	Net N (g m^{-2} $year^{-1}$)	3.05	3.32	3.33	3.32	3.01	3.26	3.21	3.21
	Removal N (g m^{-2} $year^{-1}$)	25.97	25.63	25.49	23.84	23.90	23.55	23.39	22.26
	Ecosystem-C (Mg ha^{-1})	83.24	124.40	152.34	176.06	115.63	161.05	189.92	212.84
WTH	AG-Biomass (Mg C ha^{-1})	7.94	17.28	24.34	24.77	7.55	15.19	23.70	23.71
	Soil-C (Mg ha^{-1})	20.93	21.87	23.21	22.49	43.04	43.35	46.00	44.43
	Net N (g m^{-2} $year^{-1}$)	1.95	1.73	1.73	1.66	2.23	2.01	1.97	1.88
	Removal N (g m^{-2} $year^{-1}$)	25.35	25.18	25.02	23.78	23.18	22.90	22.87	21.83
	Ecosystem-C (Mg ha^{-1})	50.12	61.31	72.72	71.10	81.79	89.95	105.56	101.59

Values are an average for a 300-year simulation. AG-Biomass, Soil-C, Net N, removal N, Ecosystem-C refer to above-ground biomass, total soil carbon, net N mineralization, removal nitrogen, and total ecosystem carbon, respectively.

young forest under current harvesting operation and use conditions would add C source to atmosphere, although the creation of new forests on deforested area will increase C sink in forest ecosystem. Kurz et al. (1998) discussed the effects of transitions between natural and managed forests on net C flows in boreal systems and pointed out the importance of the natural disturbance return period relative to the harvest interval.

Removal of total ecosystem C by different harvesting regimes estimated by Morrison et al. (1993) for two major tree species of the boreal forest region in Ontario showed that CH would result in about 20–33% C loss from sites, with more intensive harvesting regimes removing up to 35–44%. Results of the simulation reported here indicate that reducing harvesting intensity and extending rotation length would be beneficial for long-term C sequestration for this area of Canadian boreal forest—the C sink could be increased by as much as 36–40%.

It is well recognized that WTH produces significantly higher removal of biomass than CH of the same stand, however, these increases are accompanied by greater removal of nutrients, due to the removal of nutrient-rich foliage and small branches. As a consequence, WTH may threaten the long-term productivity of nutrient-poor sites. Using the ecosystem model FORECAST, Kimmins and Scoullar (1995) reported that WTH could decrease the biomass productivity of a Douglas-fir stand up to 20% over three consecutive 80-year rotations. Wei et al. (1997) also found that WTH could decrease the biomass productivity of lodgepole pine forest up to 25% after four consecutive 60-year rotations, but that the effects could be reduced by interplanting N-fixing Sitka alder. Simulations of spruce stands over a 300-year period indicated that productivity (measured as harvested stem biomass) decreased with increasing harvesting intensities, whereas total harvested biomass increased with increased harvesting intensities in more productive stands (Bengtsson and Wiström, 1993). Our simulations with CENTURY 4.0 in this study (Table 3) suggest that total long-term forest productivity (using aboveground biomass as the indicator) and N availability would be reduced by about 40–42% and 36–41%, respectively, with increasing harvesting intensity (CH vs. WTH). However, net loss of forest productivity would be higher in higher productivity forest stands in low boreal ecoclimatic regions (e.g. Prince Albert).

SOM plays an important role in supporting soil nutrient availability, which maintains site productivity, particularly in N-limited boreal forest ecosystems. It has been assumed that forest harvesting causes a loss of as much as 20–50%

of the organic C after forest harvesting (e.g. Houghton et al., 1983). Covington (1981) reported that the organic matter content of the O horizon in northern hardwoods decreased to about 50% of the original content 15 years after cutting. Predictions by Aber et al. (1978) indicate that harvesting lowers both N availability and forest floor organic matter for 15–30 years following cutting. Other studies show very little change (±10%) in soil C with harvesting (Johnson, 1992; Bengtsson and Wiström, 1993). The present results (Table 3) indicate that soil C is reduced by about 32% after intensive harvesting compared with CH. The results seem to be site specific, because two studied sites (e.g. Prince Albert and Thompson) are located in the boreal forest biome which contains high soil C storage relative to other biomes (Apps et al., 1993). Since soil N content in forests generally correlates well with SOM, harvesting can result in large losses of soil N. Increased residue removal with WTH and shorter rotations may exacerbate N loss from the site (Jurgensen et al., 1980, 1997). Results of the present study results (Tables 3 and 5) are qualitatively consistent with these results. However, impacts of fire, site preparation and changes in forest cover type on C and N dynamics were not taken into account in the present work. Further investigation of these potential effects on forest ecosystem C and N should be performed, but are beyond the objectives of this study.

5. Conclusion

Human disturbances from intensive harvesting significantly affect forest growth, and C and N dynamics. In the absence of long-term field trials, a process-based ecosystem model (such as CENTURY 4.0) may provide an alternative means of examining the long-term effects of management on C and N dynamics of future Canadian boreal ecosystems. The key features of CENTURY include the explicit partitioning of living biomass and dead organic matter into compartments defined by differing turnover times, the high degree of integration between biophysical and biogeochemical processes, and the feedbacks between above-ground (plant) and below-ground (soil) via N availability. The results presented in this study suggest that total ecosystem C and N availability would decrease under increasingly intensive harvesting (e.g. WTH). A shift from CH to WTH in boreal forests would increase in N loss, potentially resulting in long-term reductions in site productivity. Increasing harvesting intensity would also decrease soil C storage, but these impacts would be less in high boreal ecoclimatic regions having higher soil organic stocks than in low boreal ecoclimatic regions. Total ecosystem C is highest under long (120-year) rotations and is reduced under shorter (60- and 30-year) rotations. However, shortened rotations result in a greater loss of N from the ecosystem. Reducing harvesting intensity and extending rotation length could enhance the long-term capacity of Canadian boreal forest ecosystems to sequester C. Further investigation of the effects of site preparation and changes in forest cover type on C and N dynamics would improve our understanding of the effects of harvesting on Canadian boreal forest ecosystems.

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References

Agriculture Canada Expert Committee on Soil Survey, 1987. The Canadian System of Soil Classification, second ed. Agric. Can. Ottawa, Ontario, Canada, Publ. 1459.

Aber, J.D., Botkin, D.B., Melillo, J.M. 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Can. J. For. Res. 8, 306–315.

Aber, J.D., Melillo, J.M., Federer, C.A. 1982. Predicting the effects of rotation length, harvesting intensity and fertilization on fiber yield from northern hardwood forests in new England. For. Sci. 28, 31–45.

AES, 1983, Atmospheric Environment Service (AES). Canadian Climate Normals 1950-1980, Temperature and Precipitation, Prairie Provinces, Environment Canada, Downsview, Ontario.

Apps, M.J., Price, D.T., 1996. Chapter 1: Introduction. In: Apps, M.J., Price, D.T. (Eds.), Forest Ecosystems, Forest Management and the Global Carbon Cycle, NATO ASI Series I (Global Environmental Change), vol. I 40. Springer-Verlag Academic Publishers, Heidelberg, pp. 19–24.

Apps, M.J., Kurz, W.A., Luxmoor, R.J., Nilsson, L.O., Sedjo, R.A., Schmidt, R., Simpson, L.G., Vinson, T.S. 1993. Boreal forest and tundra. Water Air Soil Pollut. 70, 39–53.

Apps, M.J., Bhatti, J.S., Halliwell, D.H., Jiang, H., Peng, C.H. 2000. Simulated carbon dynamics in the boreal forest of central Canada under uniform and random disturbance regimes. In: Lal, R.L., Kimble, J.M., Stewart, B.A. (Eds.), Global Climate Change and Cold regions Ecosystems, pp. 107–122.

Bengtsson, J., Wiström, F. 1993. Effects of whole-tree harvesting on the amount of soil carbon: model results. New Zealand J. For. Sci. 23, 380–389.

Bolker, B.M., Pacala, S.W., Parton, W.J. 1998. Linear analysis of soil decomposition: insights from century model. Ecol. Appl. 8, 425–439.

Boyle, J.R. 1976. A system for evaluating potential impacts of whole tree harvesting on site quality. Tappi 59, 79–81.

Boyle, J.R., Phillips, J.J., Ek, A.R. 1973. Whole-tree harvesting: nutrient budget evaluation. J. For. 71, 760–762.

Chen, J.M., Chen, W., Liu, J., Cihlar, J. 2000. Annual carbon balance of Canada's forests during 1895–1996. Global Biogeochem. Cycles 14, 839–849.

Comins, H.N., McMurtrie, R.E. 1993. Long-term response of nutrient-limited forests to CO_2-enrichment; equilibrium behaviour of plant-soil models. Ecol. Appl. 3, 666–681.

Cooper, C.F. 1983. Carbon storage in managed forests. Can. J. For. Res. 13, 155–166.

Covington, W.W. 1981. Changes in forest floor organic matter and nutrient content following clear -cutting in northern hardwoods. Ecology 62, 41–48.

Dewar, R.C. 1990. A model of carbon storage in forests and forest products. Tree Physiol. 6, 417–428.

Dewar, R.C. 1991. Analytical model of carbon storage in trees, soils, and wood products of managed forests. Tree Physiol. 8, 239–258.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystem. Science 263, 185–190.

Dyck, W.J., Cole, D.W. 1994. Strategies for determining consequences of harvesting and associated practices on long-term productivity. In: Dyck, W.J., Cole, D.W., Comerford, N.B. (Eds.), Impacts of Forest Harvesting on Long-Term Site Productivity. Chapman and Hall, London, pp. 13–40.

Freedman, B., 1981. Intensive forest harvest: a review of nutrient budget consideration. Can. For. Serv., Marit. For. Res. Cent., Inf. Rep. M-X-121.

Friend, A.D., Stevens, A.K., Knox, R.G., Cannell, M.G.R. 1997. A process-based, biogeochemical, terrestrial biosphere model of ecosystem dynamics (HYBRID v3.0). Ecol. Model. 95, 249–287.

Gordon, A.G., 1983. Nutrient cycling dynamics in differing spruce and mixedwood ecosystems in Ontario and the effects of nutrient removals through harvesting, In: Wein, R.W., Riewe, R.R., Methven, I.R., (Eds.), Proceeding of Resources and Dynamics of Boreal Zone, Ontario. Assoc. Can. Univ. for North. Studies, Ottawa, Ont., pp. 97–118.

Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J., Stow, T.K. 1998. Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. J. Geophys. Res. 102, 29029–29041.

Halliwell, D.H., Apps, M.J., 1997a. BOREAS biometry and auxiliary sites: Locations and descriptions, Northern Forestry Centre, Natural Resources Canada, Canadian Forest Service, Edmonton, AB, p. 120.

Halliwell, D.H., Apps, M.J., 1997b. BOREAS biometry and auxiliary sites: Overstory and understory data, Northern Forestry Centre, Natural Resources Canada, Canadian Forest Service, Edmonton, AB, p. 254.

Halliwell, D.H., Apps, M.J., 1997c. BOREAS biometry and auxiliary sites: Soils and detritus data. Northern Forestry Centre, Natural Resources Canada, Canadian Forest Service, Edmonton, AB, p. 235.

Halliwell, D.H., Apps, M.J., Price, D.T. 1995. A survey of the forest site characteristics in a transect through the central Canada boreal forest. Water Air Soil Pollut. 82, 257–270.

Harmon, M.E., Ferrell, W.K., Franklin, J.F. 1990. Effects of carbon storage of conversion of old-growth forests to young forests. Science 247, 699–702.

Hendrickson, O.Q., Burgess, D.M., Chatarpaul, L. 1987. Biomass and nutrients in Great Lakes-St. Lawrence forest species: implications for whole-tree and conventional harvest. Can. J. For. Res. 17, 210–218.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R., Woodwell, G.M. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecol. Monogr. 53, 235–262.

Jiang, H., Apps, M.J., Peng, C.H. 1999. Modeling the effects of fire disturbances on carbon dynamics of boreal forests in central Canada. In: Veenam, T.S., Smith, D.W., Purdy, B.G., Salkie, F.J., Larkin, G.A. (Eds.), The 1999 Sustainable Forest Management Network Conference: Science and Practice-Sustaining the Boreal Forest. University of Alberta, Edmonton, Canada, pp. 393–404.

Jiang, H., Apps, M.J., Peng, C.H., Zhang, Y., Liu, J., 2002. Modelling the influence of harvesting on Chinese boreal forest carbon dynamics. For. Ecol. Manage. (in press).

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. Water Air Soil Pollut. 64, 83–120.

Jurgensen, M.F., Harvey, A.E., Graham, R.T., Page-Dumroese, D.S., Tonn, J.R., Larsen, M.J., Jain, T.B. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. For. Sci. 43, 234–251.

Jurgensen, M.F., Larsen, M.J., Harvey, A.E., 1980. Microbial processes associated with nitrogen cycling in northern Rocky Mountain forest soils. P. 175–187 in environmental consequences of timber harvesting in Rocky Mountain coniferous forests. USDA For. Serv. Gen. Tech. Rep. INT-90.

Keenan, R.J., Kimmins, J.P. 1993. The ecological effects of clear-cutting. Environ. Rev. 1, 121–144.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole tree harvesting. For. Ecol. Manage. 1, 169–183.

Kimmins, J.P., Scoullar, K.A., 1995. Incorporation of nutrient cycling in the design of sustainable, stand-level, forest management system using the ecosystem management model FORECAST and its output format FORTOON. In: Nilsson, L.O., (Ed.), Nutrient Uptake and Cycling in Forest Ecosystem. Ecosystem Res. Rep. No. 13, EUR 15465.

Koch, G.W., Scholes, R.J., Steffen, W.L., Vitousek, P.M., Walker, B.H., (Eds.), 1995. The IGBP Terrestrial Transects: Science Plan, International Geosphere–Biosphere Program Report No. 36, Stockholm, Sweden, p. 61.

Kurz, W.A., Beukema, S.J., Apps, M.J. 1998. Carbon budget implication of the transition from natural to managed disturbance regimes in forest landscapes. Mitig. Adapt. Strat. Global Change 2, 405–421.

Linklater, D. 1995. First nation's perspective on the boreal forest. Water Air Soil Pollut. 82, 525–526.

Marland, G., Marland, S. 1992. Should we store carbon in trees. Water Air Soil Pollut. 64, 181–195.

Metherell, A.K., Harding, L.A., Cole, C.V., Parton, W.J., 1993. CENTURY soil organic matter model environment, technical documentation, Agroecosystem Version 4.0. Great Plains System Research Unit, Technical Report No. 4. USDA-ARS, Fort Collins, Colorado, p. 250.

Mikhailova, E.A., Bryant, R.B., Degloria, S.D., Post, C.J., Vassenev, I.I. 2000. Modelling soil organic matter dynamics after conversion of native grassland to long-term continuous fallow using the century model. Ecol. Model. 132, 247–257.

Morrison, I.K., Foster, N.W., Hazlett, P.W. 1993. Carbon reserves, carbon cycling, and harvesting effects in three mature forests types in Canada. New Zealand J. For. Sci. 23, 403–412.

Morris, D.M., Kimmins, J.P., Duckert, D.R. 1997. The use of soil organic matter as a criterion of the relative sustainability of forest management alternatives: a modelling approach using FORECAST. For. Ecol. Manage. 94, 61–78.

Olsson, B.A., Staaf, H., Lundkvist, H., Bengtsson, J., Rosén, K. 1996. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. For. Ecol. Manage. 82, 19–32.

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

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J.-C., Seastedt, T., Garcia Moya, E., Kamnalrut, A., Kinyamario, J.I. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7, 785–809.

Peng, C.H., Apps, M.J. 1998. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in the Central of Canada: II sensitivity to climate change. Global Biogeochem. Cycles 12, 393–402.

Peng, C.H., Apps, M.J. 1999. Modeling response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecol. Model. 122, 175–193.

Peng, C.H., Apps, M.J., Price, D.T., Nalder, I.A., Halliwell, D. 1998. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in the Central of Canada: I model testing. Global Biogeochem. Cycles 12, 381–392.

Peng, C., Liu, Jinxun, Dang, Qinglai, Apps, Michael J., Jiang, Hong, 2002. TRIPLEX: A generic hybrid model for predicting forest growth, and carbon and nitrogen dynamics. Ecol. Model. (in press).

Pennock, D.J., van Kessel, C. 1997. Effect of agriculture and of clear-cut forest harvest on landscape-scale soil organic carbon storage in Saskatchewan. Can. J. Soil Sci. 77, 211–218.

Prentice, I.C., Sykes, M.T., Cramer, W. 1993. A simulation model for the transient effects of climate change on forest landscapes. Ecol. Model. 65, 51–70.

Price, D.T., Apps, M.J. 1995. The boreal forest transect case study: global change effects on ecosystem processes and carbon dynamics in boreal Canada. Water Air Soil Pollut. 82, 203–214.

Price, D.T., Mair, R.M., Kurz, W.A., Apps, M.J. 1997. Comprehensive assessment of carbon stocks and fluxes in a Boreal–Cordilleran forest management unit. Can. J. For. Res. 27, 2005–2016.

Price, D.T., Peng, C.H., Apps, M.J., Halliwell, D. 1999. Simulating effects of climate change on boreal ecosystem carbon pools in central Canada. J. Biogeogr. 26, 1237–1248.

Roff, C., Ågren, G.I. 1999. Predicting effects of different harvesting intensities with a model of nitrogen limited forest growth. Ecol. Model. 118, 193–211.

Scoggan, H.J., 1979. The Flora of Canada. Four volumes, Publ. Bot. 7, Natl. Mus. Can. Nat. Mus. Nat. Sci. Ottawa, Ontario, Canada.

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. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, p. 37.

Wei, X.H., Peng, C.H., Kimmins, J.P. 1997. Impacts of intensive timber harvesting on sustainability of long-term site productivity. In: Chen, X., Dai, X., HuTao, T. (Eds.), Eco-environmental Research and Sustainable Development. China Environmental Sciences Press, Beijing, China, pp. 343–368.