Application of the forest ecosystem model EFIMOD 2 to jack pine along the Boreal Forest Transect Case Study

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Shaw, C., Chertov, O., Komarov, A., Bhatti, J., Nadporozskaya, M., Apps, M., Bykhovets, S. and Mikhailov, A. 2006. **Application of the forest ecosystem model EFIMOD 2 to jack pine along the Boreal Forest Transect Case Study.** Can. J. Soil Sci. **86**: 171–185. Sustainability of forest ecosystems and climate change are two critical issues for boreal forest ecosystems in Canada that require an understanding of the links and balance between productivity, soil processes and their interaction with natural and anthropogenic disturbances. Forest ecosystem models can be used to understand and predict boreal forest ecosystem dynamics. EFIMOD 2 is an individual tree model of the forest-soil ecosystem capable of modelling nitrogen feedback to productivity in response to changes in soil moisture and temperature. It has been successfully applied in Europe, but has not been calibrated for any forest ecosystem in Canada. The objective of this study was to parameterize and validate EFIMOD 2 for jack pine in Canada. Simulated and measured results agreed for changes in tree biomass carbon and soil carbon and nitrogen with increasing stand age and across a climatic gradient from the southern to northern limits of the boreal forest. Preliminary results from scenario testing indicate that EFIMOD 2 can be successfully applied to predict the impacts of forest management practices and climate change in the absence of natural disturbances on jack pine in the boreal forest of Canada. Model development is underway to represent the effects of natural disturbances.

Key words: EFIMOD 2, forest soil, carbon, nitrogen, model, jack pine

Shaw, C., Chertov, O., Komarov, A., Bhatti, J., Nadporozskaya, M., Apps, M., Bykhovets, S. et Mikhailov, A. 2006. **Application du modèle de l'écosystème forestier EFIMOD 2 au pin gris le long du transect de la forêt boréale**. Can. J. Soil Sci. **86**: 171–185. La pérennité des écosystèmes forestiers et le changement climatique sont deux éléments d'importance capitale pour les écosystèmes forestiers du Canada. Pour bien les saisir, il importe de comprendre les liens et l'équilibre entre la productivité et les processus du sol, ainsi que leurs interactions avec les perturbations naturelles et anthropiques. On peut se servir de modèles de l'écosystème forestier pour analyser et prévoir la dynamique de l'écosystème de la forêt boréale. EFIMOD 2 est un modèle de l'écosystème forêts-sol reposant sur un seul arbre. Il reproduit la rétroaction de l'azote par rapport à la productivité consécutivement à une modification de la teneur en eau et de la température du sol. On s'en est servi avec succès en Europe, mais le modèle n'a pas été étalonné pour les écosystèmes forestiers canadiens. La présente étude avait pour but de paramétrer et de valider ce modèle pour le pin gris, au Canada. Les résultats obtenus par simulation et sur le terrain concordent quant à la modification, d'une part, de la quantité de carbone contenue dans la biomasse des arbres et, d'autre part, de la concentration de carbone et d'azote dans le sol attribuable au vieillissement des peuplements, le long du gradient climatique allant de la limite sud à la limite nord de la forêt boréale. Les résultats préliminaires des essais effectués selon divers scénarios indiquent qu'on peut efficacement se servir du modèle EFIMOD 2 pour prévoir l'incidence des pratiques d'aménagement forestier et du changement climatique sur les peuplements de pin gris de la forêt boréale canadienne en l'absence de perturbation naturelle. Le modèle est en train d'être perfectionné afin de tenir compte des effets des perturbations naturelles.

Mots clés: EFIMOD 2, sol forestier, carbone, azote, modèle, pin gris

Sustainability of forest ecosystems (Gessel et al. 1990; Boyle and Powers 2001; Burton et al. 2003) and climate change (Apps et al. 2002; Shaw and Apps 2002; Karjalainen et al. 2002; Stocks et al. 2002) are two critical issues for boreal forest ecosystems in Canada. Both require an understanding of the links and balance between productivity, soil processes and their interaction with natural (fire, insect outbreaks) and anthropogenic (harvest practices, fire suppression) disturbances (Kurz and Apps 1999). Forest ecosystem models are useful to test and develop our understanding of boreal forest ecosystems and are required to meet the demand from policy makers and managers to predict the impacts of different scenarios for climate change and forest management practices (Sampson et al. 2000; Messier et al.

Abbreviations: **BERMS**, Boreal Ecosystem Research and Monitoring Sites; **BFTCS**, Boreal Forest Transect Case Study; **DBH**, diameter at breast height; **H**, height; **MAT**, mean annual temperature; **MSPpt**, mean summer precipitation; **MWPpt**, mean winter precipitation; **NPP**, net primary production; **REMS**, root error mean square; **SFMN**, Sustainable Forest Management Network; **SPE**, single plant ecosystem

2003). Models can be used not only to examine the impacts of climate change or management practices independently, but also to look at their complex interactions. Because simulation models are the only tool currently available to make predictions about impacts of global changes and management practices into the future, it is important they be carefully verified, calibrated and validated for the ecosystem under consideration prior to scenario testing.

EFIMOD 2 is a process-based forest ecosystem model that was developed in Europe and has been extensively tested and utilized in Finland, Germany and Russia (Chertov et al. 1999a; Komarov et al. 2003). It is an individual-tree model that integrates vegetation and soil processes over a stand's development and can be used to simulate carbon dynamics. Of the different types of models used for understanding and prediction in boreal forest ecosystems discussed by Messier et al. (2003) EFIMOD 2 is most similar to FORCYTE-FORECAST that is described as a net primary productivity model.

In EFIMOD 2 the processes of soil organic matter transformation are the principal driving variables in the model. The model structure contains explicit feedbacks between the tree and soil where annual additions of litter combined with soil organic matter decompose to release nitrogen that is made available for uptake by the trees. Decomposition rates depend on a variety of factors including soil moisture and temperature, C:N ratio and the quality of the soil organic matter (degree of humification). EFIMOD 2 is a combined model comprised of two sub-models, one for the soil and one for trees. The structure of the soil sub-model explicitly includes the influence of soil microbiota and soil fauna on the rates of organic matter decomposition that are reflected in the turnover rates of different humus forms (Chertov et al. 2001). The tree growth sub-model simulates stand dynamics in a way that allows for detrital inputs to vary in quality and quantity over the span of stand development. The model requires climatic input based on long-term climatic data and currently this input is generated by SCLISS (Bykhovets and Komarov 2002) a soil-climate simulator that predicts monthly soil moisture and temperature using the best available long-term climatic data. SCLISS accounts for the effect of canopy cover and the different moisture retention characteristics of the forest floor and mineral soil.

EFIMOD 2 has several practical features that appeal to potential users. It can be parameterized from data available in the published literature, the structure is flexible so that it can be readily adapted to different ecosystems, modelled outputs are variables that can be measured in the field providing a mechanism for validation and the model has a user-friendly interface that facilitates rapid communication between the model developers and users.

EFIMOD 2 has been used to predict the response of European boreal forest ecosystems to climate change, management practices and anthropogenic impacts such as atmospheric nitrogen deposition (Chertov et al. 1999b, 2002; Van Oijen et al. 2006) but has not been calibrated or tested for Canadian boreal forest ecosystems where productivity and decomposition of organic matter are limited by short growing seasons, low temperatures, low nitrogen availability and extremes in soil moisture content (Kimmins 1996). In order to use EFIMOD 2 to predict the impacts of climate change on forest ecosystems in Canada, the model had to be calibrated for Canadian tree species and soils and validated against measured data.

Jack pine (*Pinus banksiana*) was selected as the first test case for a Canadian boreal tree species. It is an ideal choice because of its widespread occurrence in a diversity of climate types, but a relatively narrow range of site types that could be commonly described as even-aged jack pine on well-drained sandy soils of low fertility. It is a post-disturbance pioneer species that typically grows on sandy Podzolic and Brunisolic soils developed in glacial outwash, fluvial or lacustrine parent materials (Burns and Honkala 1990). Typical soils under jack pine are well-drained with a low fertility status. Even-aged stands of fire origin are common but jack pine do occur as a component of black spruce (*Picea mariana*), paper birch (*Betula papyrifera*) and aspen (*Populus tremuloides*) forest types. In Canada, jack pine types are recognized based on associations with different types of moss, lichens, shrubs and other tree species (Burns and Honkala 1990; Farrar 1995).

In Canada, jack pine is commonly managed on a rotation age of about 70 to 90 yr (Jeglum 1994). Whole-tree harvesting is a common practice where trees are felled and skidded to the roadside (Jeglum 1994; Weetman 1998). Post-harvest sites are typically drag scarified and planted at densities ranging from 1500 to 2500 seedlings ha^{-1} (Jeglum 1994). Although commercial thinning is not a common practice in jack pine stands in Canada (Foster et al. 1995) some economic benefits may be realized from a non-commercial mid-rotation thinning if rotation age is shortened or productivity is increased (Lieffers et al. 2003).

EFIMOD 2 was calibrated using data obtained from the literature and validated using data collected along the Boreal Forest Transect Case Study (BFTCS). The BFTCS was established with the primary goal of understanding the response of boreal forest ecosystems to climate change and its interaction with natural and anthropogenic disturbances (Price and Apps 1995). Initially, the study was established with upland jack pine and black spruce along a gradient of changing climate and age classes. Over the years it has expanded to include sites for wetlands and for post-harvest and post-fire disturbances.

This paper reports on the calibration and validation of EFIMOD 2 for jack pine and includes a scenario testing of the effects of some forest management practices on productivity and soil carbon. This represents a first step toward calibration and validation of EFIMOD 2 for other boreal forest tree species and more complex scenario testing of the impacts of climate change and disturbances from harvesting and fire on forest soils in Canada.

METHODS

EFIMOD 2

Detailed descriptions of the development and application of EFIMOD 2 and its sub-component models are widely published in the scientific literature (Chertov et al. 1999a,b,

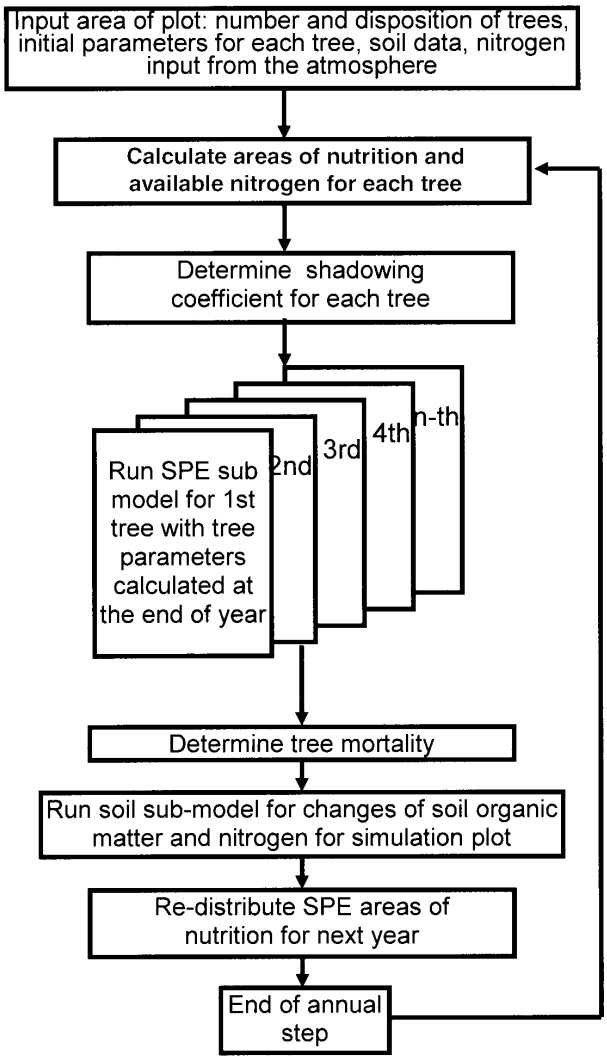

Fig. 1. Flow-chart of the EFIMOD annual time step.

2001, 2003; Komarov et al. 2003). An overview of the model's structure and features is provided below.

Conceptually EFIMOD 2 models the tree-soil system as a stand represented by a population of "single plant ecosystems" (SPE) (Fig. 1). The SPE is the basic forest ecosystem unit in the model and is defined by the space occupied by a single plant (tree) and the soil it occupies. The volume of the soil in the SPE is determined by the root mass of the tree. Individual trees compete for available light as a function of tree height (shading from nearest neighbours) and for nitrogen that becomes available from the mineralization of soil organic matter within the SPE.

The model runs on a yearly time-step (Fig. 1) and reflects the feedback between nitrogen in the soil and productivity. Every year potential growth is calculated as the maximum annual biomass increment per unit of leaf/needle biomass (α_{max}) and the nitrogen (N) required by the tree to satisfy that biomass increment (unit of N per unit of biomass increment). The maximum increment calculated for a given year is reduced by a proportion of the photosynthetically active radiation if there is competition for light due to shading, and by the pool of soil available N if the amount of N in the SPE is less than the amount required by the tree to satisfy the maximum biomass increment. The increment realized is equal to the minimum value from the increment calculated by the available light and the available soil nitrogen. N consumed from the area of nutrition of an individual tree is then reallocated amongst the trees components (i.e., foliage, roots, branches, stem) at the end of every time step.

Sensitivity analyses for EFIMOD 2 showed that the tree sub-model is highly sensitive to changes in the reallocation of the biomass increment and tree mortality functions, while the soil sub-model is sensitive to the proportion and mineralization rate of stable humus in the mineral soil. Overall the model is very sensitive to all nitrogen compartments including N required for tree growth, N withdrawal from senescent needles, soil N and N deposition from the atmosphere (Komarov et al. 2003).

EFIMOD 2: Parameterization and Calibration

EFIMOD 2 has been calibrated for six tree species in Europe including Scots pine (*Pinus sylvestris*), which was used as a starting point to calibrate the model for jack pine. Data required for parameterization of jack pine tree growth were collected from the scientific literature and government reports (Table 1). These data were used to establish a preliminary set of parameters for the model calibration. Some uncertainty surrounds parameters for jack pine where limited data were available. For example, some uncertainty is associated with the allocation of net primary production (NPP) between tree components (foliage, roots, stems, branches, etc.) because allocation coefficients were based on only two publications (Gower et al. 1997; Steele et al. 1997). Some uncertainty also surrounds the potential growth rate used to determine the maximum productivity of needles in a growing season. However, previous experience with the parameterization of EFIMOD 2 showed that the model has little sensitivity to this parameter because growth is largely governed by available soil nitrogen in the model (Chertov et al. 2003; Komarov et al. 2003).

Soil pools were initialized using data extracted from a database for Canadian forest soils (Siltanen et al. 1997). Data for total soil carbon and nitrogen and bulk density for Orthic Dystric and Eutric Brunisols and Eluviated Eutric and Dystric Brunisols under jack pine in the Boreal West were extracted from the database and used to estimate initial values for soil organic matter and nitrogen pools. Detailed soil moisture and temperature data [provided by Boreal Ecosystem Research and Monitoring Sites (BERMS) coordinator Alan Barr at University of Saskatchewan; details for data collection found at http://berms.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc] collected from 1997 to 2003 at an old jack pine site in northern Saskatchewan were used to calibrate SCLISS (Bykhovets and Komarov 2002).

Few changes to the model were required as a result of the calibration. No changes were made to the model structure and a few minor modifications were made to some of the

Table 1. Sources of data used to parameterize jack pine tree growth

Data type	Description of how data is used in the model	References
Site index curves	To compare simulated jack pine growth patterns with those derived from measured data	Huang et al. (1997) Huang (1997)
Biomass equations	To convert tree height and diameter data to tree biomass at the model initialization	Bond-Lamberty et al. (2002)
Wood density	To calculate tree diameter and height from the simulated data for stem biomass	Jessome (1977)
N content of tree components	To calculate nitrogen demand for growth of different tree components	Perala and Alban (1982) Fyles (1986) Sustainable Forest Management Network (SFMN) (2004)
Nitrogen retention from senescent needles	To calculate litter fall nitrogen content as a parameter determining the decomposition rate	SFMN (2004) Preston et al. (2006) Bhatti (unpublished data from BFTCS)
Needle and fine root life span	To calculate the needle and fine roots litter fall mass	SFMN (2004)
Ash content of litter fall	Parameter used in the soil sub-model to calculate decomposition rates	SFMN (2004)
Reallocation of NPP to tree components	To calculate the biomass increment of tree components	Gower et al. (1997) Steele et al. (1997)
Productivity of needles per growing season	To calculate potential biological productivity of jack pine needles under given bio-climatic conditions	Gower et al. (1997) Steele et al. (1997) Fassnacht and Gower (1997) Li et al. (2003)

parameters. Some calibration of NPP reallocation (α_{max}), nitrogen retention from senescent needles and initial stand density were necessary in order to assign single values to the parameters in question, but all assigned values were similar to those reported in the literature or estimated by data published in the scientific literature (Table 1).

The model uses different coefficients for NPP reallocation depending on age class. Initially reallocation coefficients were based on up to 80% of the biomass increment going to fine root growth. However, under this assumption jack pine failed to grow in the model. Therefore, after calibration, the coefficient was changed to 40% for all age classes (Table 2). Values for α_{max} were set at 3.0 and 2.7 for young and mature-aged stands and are at the upper end of values calculated from data reported in the literature that ranged from 1.1 to 2.6. Sensitivity of the EFIMOD 2 jack pine model is consistent with previous analyses (Komarov et al. 2003). For example, stem biomass is sensitive to the nitrogen concentration in needles after abscission (Fig. 2) reflecting the degree to which the plant (tree) controls growth by retention and internal reallocation of nitrogen (Nambiar and Fife 1991). Although uncertainty surrounds the initial stand density (often unknown), modelled soil carbon, nitrogen and tree stem carbon (major source of carbon input to the soil sub-model) are not very sensitive to initial stand density (Fig. 3 a,b,c).

Validation Sites and Data

Data collected at jack pine sites located in three areas along the BFTCS (Fig. 4) were used for validation of EFIMOD 2; the Candle Lake sites in Saskatchewan, and the Flin Flon and Thompson sites in Manitoba. These sites were selected to represent a gradient in climate from warm and dry in Candle Lake to cold and wet in Thompson (Fig. 4). Three 20 m × 20 m plots were established in mature stands at each of the three areas to facilitate comparisons across the climatic gradient at a similar stand age. Using the same approach (three 20 m × 20 m per site), plots were established at more sites in the Candle Lake area representing a cross section of stand ages and post-disturbance conditions. A subset of sites from Candle Lake selected to represent a sequence of stand ages along with data collected in the Candle Lake area on similar site types and published elsewhere in the literature (Halliwell and Apps 1997 a,b,c; Gower et al. 1997) were used to validate the model under one climate but across several stand ages ranging from 1 to 112 years.

Plots were located in stands dominated by jack pine where understory species include the shrubs *Vaccinium vitis-idaea*, *V. myrtilloides* and *Arctostaphylos uva-ursi*, mosses *Dicranum polysetum* and *Polytrichum* sp., and the reindeer lichens *Cladonia cornuta*, *Cladina mitis* and *C. stellaris*. Soils were classified as Eutric or Dystric Brunisols that are rapidly drained with a sandy to sandy-loam texture and pH ranging from 5.0 to 6.5 in the B horizon. Plots for mature jack pine in the Candle Lake and Thompson areas are located at the original BOReal Ecosystem-Atmosphere Study southern (S-TE-OJP) and northern (N-TE-OJP) flux tower sites, respectively (Halliwell and Apps 1997a) (N-TE-OJP is TE-OJP(1) and S-TE-OJP is POM-OJP(1) in Halliwell and Apps 1997a). The plots are located immediately outside the footprint of the towers that are still operat-

Table 2. Ecological parameters for jack pine used in EFIMOD 2

Parameters	Stem	Needles	Branches	Coarse roots	Fine roots
Nitrogen demand [g(N) g^{-1}(biomass increment) yr^{-1}]	0.0009	0.0070	0.0040	0.0016	0.0040
NPP reallocation coefficients: Young trees (< 30 yr)	0.24	0.28	0.06	0.02	0.40
Mean-aged trees (31–130 yr)	0.26	0.30	0.02	0.02	0.40
Proportion of biomass going to litter (yr^{-1})	0.00	0.21	0.0025	0.0025	0.64
Nitrogen concentration in litter fall [g(N) g^{-1}(litter)]	0.0009	0.0045	0.0040	0.0016	0.0035
Litter ash content [g(ash) g^{-1}(litter)]	0.005	0.025	0.005	0.005	0.025

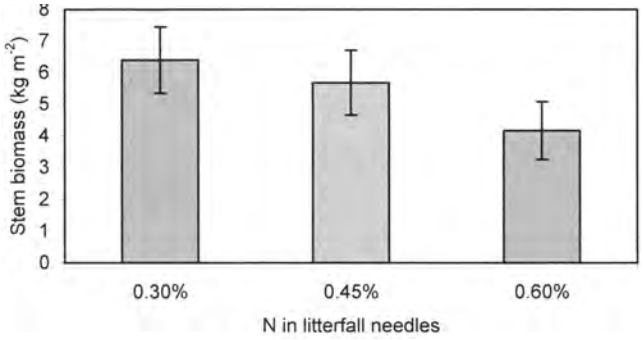

Fig. 2. Sensitivity of stem biomass simulated by EFIMOD 2 to nitrogen content in needles after abscission.

ing as part of the FLUXNET-Canada research network that evaluates ecosystem CO_2 and H_2O exchange. Data collected on the plots were used to estimate the mean and standard deviation for a variety of stand and soil characteristics that were used for comparison with the modelled output.

The diameter at breast height (DBH) (cm) and height (m) of all trees in each plot were measured to estimate stem density (stems ha^{-1}), mean stand height (m), mean stand DBH (cm) and tree biomass (t ha^{-1}). Tree biomass by component was calculated using the equations of Alban and Laidly (1982). This set of equations was chosen over others published in the literature for jack pine because it includes equations for stemwood and stembark, and that distinguish foliage from branches in the crown. Only trees with DBH > 5.0 cm were included in the stand level estimates. At each site, litter was collected in 36 plastic buckets (27.3 cm diameter and 30 cm height) with mesh bottoms, and 27 mesh quadrats were laid on the forest floor (1 m^2 with 1 cm^2 openings). The latter was designed to capture the coarser material, especially twigs. The traps were installed in June 2000 and emptied on an annual basis. Litter was sorted by component into twigs, leaves, needles cones and bark and dried at 70°C to estimate annual litterfall (g m^{-2}).

Composite soil samples were collected from each horizon in one soil pit at each plot. Each soil pit was excavated to about 1 m depth and the profiles described using the Canadian Soil Classification System (Soil Classification Working Group 1998).

In addition to samples collected from the pits, nine soil samples (forest floor and mineral soil) were taken within the plots using a systematic sampling design. Forest floor samples (a 15 cm × 15 cm square) were dried at 70°C to a constant weight to estimate forest floor mass, after removal of

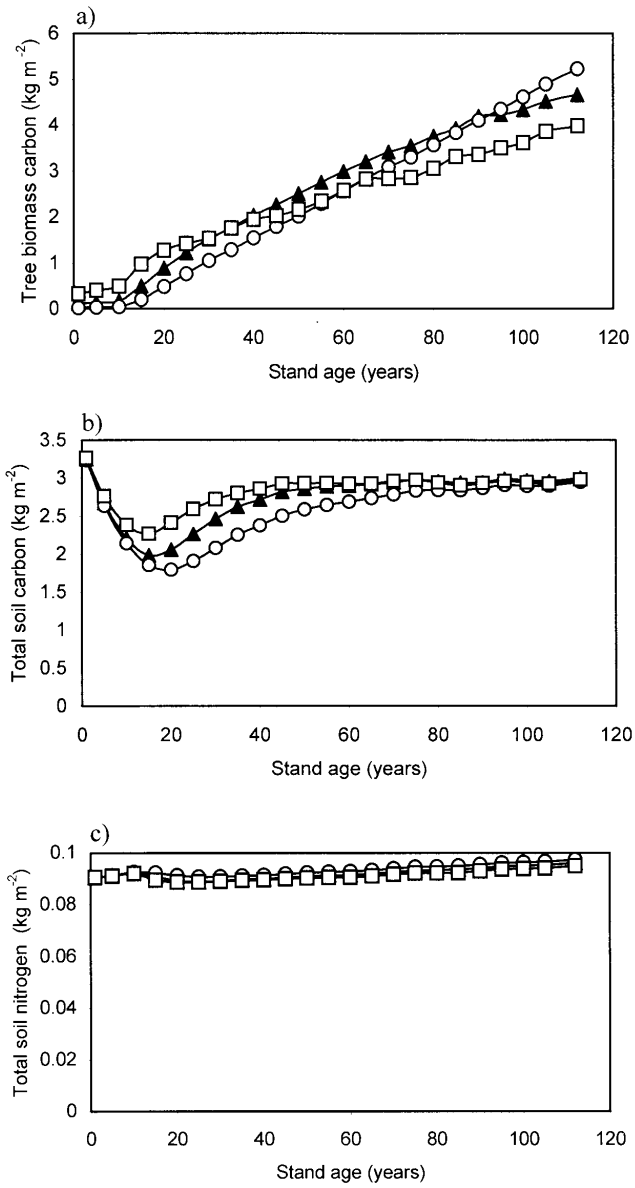

Fig. 3. Sensitivity of (a) tree biomass carbon, (b) total soil carbon and (c) total soil nitrogen, simulated by EFIMOD 2 to initial stand density. –○–, 1000 stems/ha; –▲–, 3000 stems/ha; –□–, 9000 stems/ha.

live vegetation and root. Mineral soil samples were taken at depth increments of 0–5, 5–10, 10–20 and 20–30 cm. All samples were analyzed for total carbon by dry combustion using a LECO Carbon Determinator (Model CR12) and

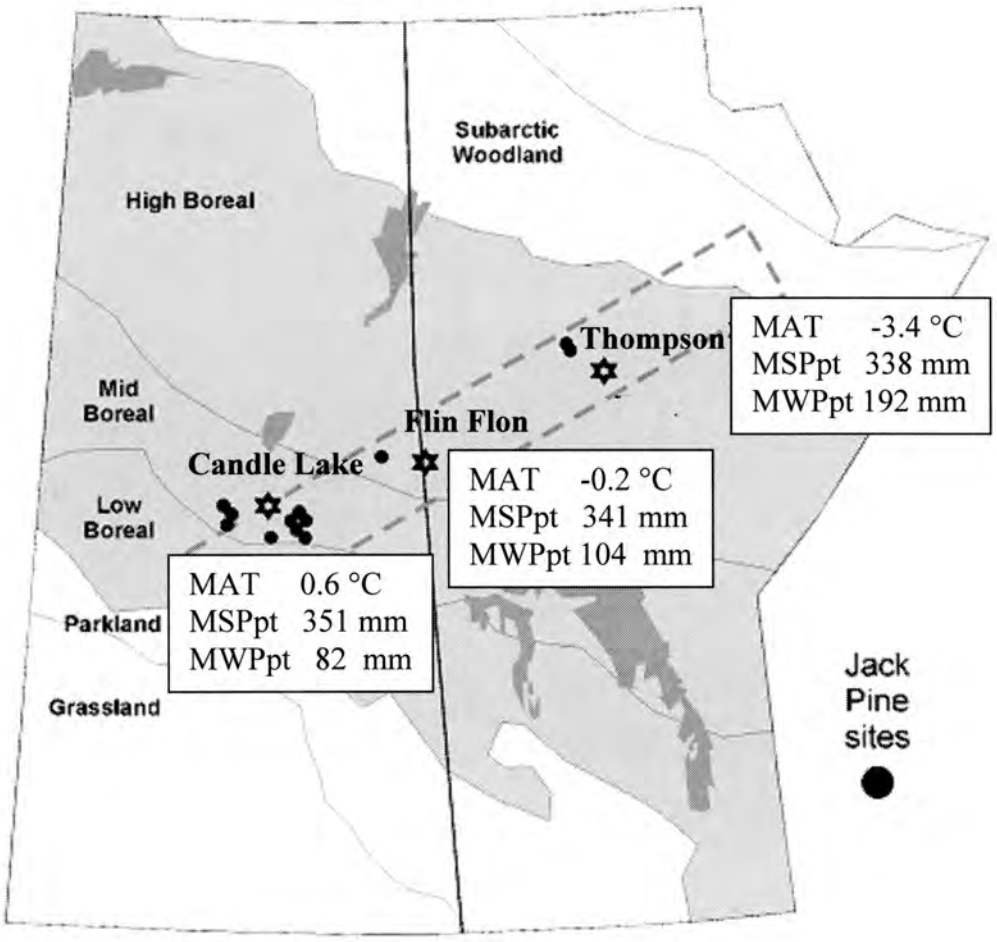

Fig. 4. Location of sites along the Boreal Forest Transect Case Study showing mean annual temperature (MAT), mean summer precipitation (MSPpt) and mean winter precipitation (MWPpt) for the Candle Lake, Flin Flon and Thompson sites.

total nitrogen using a semimicro-Kjeldahl digest following the procedure describe by Preston et al. (2002). Bulk density, and soil texture were determined on all mineral soil samples following the procedures of Kalra and Maynard (1991).

Validation Procedure

Data used for validation were not used for the parameterization and calibration, therefore providing an independent dataset for testing the model. Validation of EFIMOD 2 calibrated for jack pine was carried out for two cases. In the first case climate was kept constant and modelled results were compared with measured values for stands ranging in age from 1 to 112 yr in the Candle Lake area. Modelled results were compared with measured data collected along the BFTCS and described in this paper, as well as data collected by others in the Candle Lake area and reported in the literature (Table 3). Wherever possible the goodness-of-fit between simulated and modelled data was assessed using the ratio of the root mean square error (RMSE) to $RMSE_{95\%}$ (Smith et al. 1997). A ratio less than one indicates that the simulated values fall within the 95% confidence intervals of the measurements. In the second case, climate varied across a gradient from Candle Lake to Flin Flon and then Thompson. Modelled output was compared with measured values at similar stand ages; 90 yr for Candle Lake and 74 yr for Flin Flon and Thompson.

Model parameters for stand and soil characteristics and for initialization were the same in every case (Table 4). Long-term climate and soil moisture and temperature data from the Environment Canada meteorological station located nearest to each test site were used to produce climatic profiles representative for each site (Table 5) that were used to initialise the SCLISS sub-model. Long-term climatic data from the Nipawin, Flin Flon and Thompson meteorological stations (Environment Canada 2004) and long-term soil moisture and temperature data from the Hudson Bay, La Ronge and Thompson meteorological stations (Environment Canada 2004) were used to represent climate and soil moisture and temperature at the Candle Lake, Flin Flon and Thompson sites respectively (Environment Canada 2004).

Scenario Testing

After the calibration and validation of EFIMOD 2 for Canadian jack pine, the model was able to reflect tree-soil relationships over stand development up to an age of about

Table 3. Data used for validation of the EFIMOD 2 jack pine model along the Candle Lake chronosequence

Age (yr)	Source	Site name	Carbon (kg m^{-2}) Forest floor	Carbon (kg m^{-2}) Mineral soil	Nitrogen (kg m^{-2}) Forest floor	Nitrogen (kg m^{-2}) Mineral soil	Mineral soil depth (cm)[z]	Mean DBH (cm)	Mean H (m)	Stem carbon (kg m^{-2})
1	Bhatti[y]	SHAR02	0.10	1.75	0.014	0.0492	10	N/d	N/d	N/d
9	Bhatti	SHAR94	0.10	1.26	0.032	0.0313	15	0.8	1.7	0.10
25	Gower et. al 1997	SYJP	1.80	2.00	N/d	N/d	70	3.2	3.7	0.75
30	Bhatti	SHAR75	0.90	1.59	0.020	0.049	15	7.1	7.4	1.25
45	Bhatti	SJIH4	1.40	1.29	0.023	0.052	15	8.0	9.2	2.20
65	[x]	(mean of 4 sites)	1.40	0.68	0.032	0.021	7	15.8	14.3	3.90
90	Bhatti	STOJP	0.53	1.45	0.012	0.053	25	13.9	14.2	3.95
112	Halliwell and Apps 1997	JMM5	0.20	1.88	0.006	0.068	33	21.5	16.1	3.75

[z]No measurable organic carbon below this depth.
[y]Data collection described in this paper.
[x]Mean of four sites: (1) SOJP (Gower et. al. 1997); (2) JMM8a, (3) JMH10, (4) JMM8b (Halliwell and Apps 1997b,c).
[w]N/d, no data.

Table 4. Initialisation values for parameters for the EFIMOD 2 jack pine model

Parameter		Initial value
Stand density (trees ha^{-1})		3000
Stand age (yr)		5
Stand height (m)		0.3
Soil organic matter pools (kg m^{-2})	Forest floor	3.76
	Mineral soil	3.09
Soil nitrogen pools (kg m^{-2})	Forest floor	0.026
	Mineral soil	0.066
Carbon:Nitrogen	Forest floor	72
	Mineral soil	23
Nitrogen input from atmosphere (kg ha^{-1} yr^{-1})	Peng et al. (1998)	2.04
Soil bulk density (g cm^{-3})		1.24
Soil moisture retention characteristics (vol/vol)%	Permanent wilting point	2.9
	Field capacity	8.8
	Saturation	26.5

Table 5. Meteorological parameters for the initialisation of the climate generator SCLISS

Site	Parameter[z]	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual total
Candle Lake	Ta	–18.8	–15.5	–9.0	2.5	10.7	15.4	17.8	15.9	10.1	3.2	–7.9	–17.0	
	Ta(SD)[y]	3.9	4.1	2.9	2.6	2.0	1.4	1.1	1.9	1.4	1.3	3.9	3.9	
	Pa	14.1	11.9	19.6	22.6	53.6	72.5	67.4	63.2	44.8	27.7	19.0	16.4	432.8
	P(CV)[x]	0.54	0.48	0.59	0.60	0.56	0.43	0.34	0.54	0.38	0.63	0.76	0.37	
	P(SD.)	*7.6*	*5.7*	*11.5*	*13.5*	*30.2*	*31.3*	*23.2*	*34.1*	*16.9*	*17.5*	*14.5*	*6.0*	
	Ts	–2.9	–2.8	–1.6	1.7	10.0	15.6	17.8	16.7	11.8	5.3	0.4	–2.2	
	Ts (SD)	0.9	0.8	0.5	0.5	3.0	4.7	5.3	5.0	3.5	1.6	0.1	0.7	
Flin Flon	Ta	–21.5	–17.3	–10.0	0.7	9.0	14.8	18.4	16.8	9.8	2.9	–8.6	–17.7	
	Ta(SD)	4.0	3.6	3.0	2.6	2.0	1.6	1.3	1.6	1.8	2.3	3.2	3.8	
	Pa	19.0	17.8	21.1	19.6	39.2	65.3	71.6	61.6	54.5	29.2	24.3	22.2	445.4
	P(CV)	0.41	0.48	0.51	0.62	0.63	0.53	0.45	0.54	0.52	0.55	0.51	0.35	
	P(SD)	*7.8*	*8.6*	*10.8*	*12.1*	*24.5*	*34.4*	*32.2*	*33.4*	*28.1*	*16.0*	*12.4*	*7.8*	
	Ts	–1.4	–2.0	–1.3	0.6	7.4	13.9	17.2	16.3	11.1	4.5	0.4	–0.6	
	Ts (SD)	0.4	0.6	0.4	0.2	2.2	4.2	5.1	4.9	3.3	1.3	0.1	0.2	
Thompson	Ta	–25.1	–20.8	–13.2	–2.4	6.3	12.2	15.6	13.8	7.1	–0.1	–11.9	–22.2	
	Ta(SD)	3.5	3.3	3.0	2.8	2.3	1.7	1.5	2.0	1.8	1.8	3.6	4.1	
	Pa	20.1	14.0	20.7	29.4	45.5	72.3	81.5	74.6	64.2	46.9	32.8	28.0	529.9
	P(CV)	0.41	0.45	0.50	0.61	0.53	0.44	0.54	0.43	0.55	0.38	0.56	0.51	
	P(SD)	*8.3*	*6.3*	*10.3*	*18.0*	*24.2*	*31.7*	*43.7*	*31.7*	*35.2*	*17.7*	*18.4*	*14.2*	
	Ts	–3.1	–3.6	–3.2	–0.9	5.1	11.6	15.5	14.5	9.0	3.1	–0.1	–2.2	
	Ts (SD)	0.9	1.1	0.9	0.3	1.5	3.5	4.6	4.4	2.7	0.9	0.0	0.7	

[z]Ta and Ta(SD), air temperature (degrees centigrade) and its standard deviation; Pa, P(CV), and P(SD), precipitation (mm), its coefficient of variation and its standard deviation; Ts and Ts(SD), soil temperature (degrees centigrade), and its standard deviation at 10 cm deep under grass.
[y](CV) coefficient of variation.
[z](SD) standard deviation.

70 yr and could reflect trends in response to climate change, in the absence of natural disturbances, reasonably well. Using the model it is possible to predict the effects of a warming climate on jack pine at the Candle Lake site and to guide the selection of effective forest management practices balancing the tradeoffs between increases in stem biomass for commercial harvesting and storage of carbon in soil to mitigate climate change. This preliminary evaluation includes the effects of a warming climate, but does not include the effects of natural disturbance regimes responding to a change in climate. As well, this preliminary evaluation does not include important considerations related to implementation, economics or policy.

Scenarios were constructed to examine the interaction between stand management practices in jack pine under the current climate and that projected by the Climatic Research Unit, University of East Anglia, UK (http://www.cru.uea.ac.uk/cru/data) in the area of the Candle Lake sites. Different management scenarios were simulated over two 70-yr rotations with a 5-yr break in between rotations to account for the time lag in regeneration (total of 145 yr). Stands were initiated at a density of 2500 trees ha^{-1} consistent with current planting practices. The following management scenarios were simulated under the current and projected climates.

1. Clear-cut at age 70 with all tree residues remaining on site.
2. Clear-cut at age 70 with all tree residues removed from the site.
3. Mid-rotation thinning at age 40, clear-cut at age 70 with all tree residues remaining on site.
4. Mid-rotation thinning at age 40, clear-cut at age 70 with all tree residues removed from the site.

The current climate scenarios were generated by SCLISS as previously described in this paper. The high-resolution global gridded dataset CRU TS 2.02 (http://www.cru.uea.ac.uk/cru/data), taken to represent the current climate predicted for the Candle Lake sites (53°15′N 103°45′W), was compared with corresponding data from the appropriate meteorological station. Differences between the projected current climate and measured current data were used to adjust the projected climate from the grid point dataset. The most dramatic climate change scenario (TYN SC 2.02) (http://www.cru.uea.ac.uk/cru/data) was chosen to estimate the consequences of an extreme climate warming. Current climatic parameters projected for the grid points were within 1°C for air temperature and within 10% for precipitation and the resulting projected change in climate for Candle Lake was a 6.1°C increase in mean annual temperature and a 51 mm increase in annual precipitation. The SCLISS model was used only to estimate soil temperature and moisture for the climate change scenarios. Results from the end of the simulation for scenario 1 (clear-cut with all tree residues remaining on the site) under the current climate was used as the standard to which all other scenarios were compared.

RESULTS

Validation of EFIMOD 2

Across Stand Age

Modelled results for stand characteristics (DBH, height and tree stem carbon) across stand ages at Candle Lake were in relatively good agreement with measured values (Fig. 5a–c). Although modelled values were close to or within the error bars for the measured values, modelled values for tree stem carbon were sometimes lower than measured values (Fig. 5c). However, the ratio of $REMS/REMS_{95\%}$ for tree stem carbon was 0.509 indicating a good fit of the modelled to the measured data.

Modelled and measured values for litter-fall biomass (needles + branches) were very similar ($REMS/REMS_{95\%} = 0.418$) indicating the model accurately reflects transfers of litter from above- (tree) to below-ground (soil) detrital pools (Fig. 6).

Measured values for forest floor carbon and nitrogen were low for young-aged stands (1, 9 yr), relatively constant between the stand ages of 25 to 65 yr and low for old-aged stands (Fig. 7 a, b). After a decline from the initialization value, modelled results for carbon and nitrogen in the forest floor were relatively constant in a pattern comparable with the period between 25 and 65 yr for the measured values. These results are generally in agreement with the findings of Howard et al. (2004) who observed little change in forest floor carbon in similar jack pine stands ranging in age from 0 to 79 yr. Modelled and measured values for total nitrogen and total carbon do not correspond well at very young stand ages (1, 9 yr) and this may be attributable to the effect of the most recent disturbance on measured values that are not reflected in the model. Modelled estimates for forest floor carbon and nitrogen were lower than measured between the stand ages of 25 to 65 yr. Values for the ratio $REMS/REMS_{95\%}$ for total carbon and total nitrogen in the forest floor were 1.266 and 1.246, respectively, indicating a poor fit of modelled to measured data. However, when the recently disturbed young-aged stands were removed from the goodness-of-fit test, the values for the ratio dropped to 0.682 and 0.825, respectively, indicating a good fit for modelled to measured data between the stand ages of 25 and 65 yr. The model was able to reflect the relationship between carbon and nitrogen very well up to about 45 yr of age, after which modelled and measured results diverged (Fig. 7c). However, a ratio of $REMS/REMS_{95\%}$ of 0.611 for the C:N ratio indicated an overall good fit of modelled to measured data.

Measured values for mineral soil carbon and nitrogen were highly variable and did not exhibit any discernable trend over stand age (Fig. 8 a, b). Generally results predicted by the model for mineral soil carbon fell within the range of measured values (Fig. 8a). The model tended to overestimate mineral soil N but the estimates were often within the range of error for the measured values (Fig. 8b). Estimates from measured data for C:N in the mineral soil were highest at low stand ages (1, 9 yr), and levelled off to a relatively constant C:N of about 25 across the remaining stand ages (Fig. 8c). Generally, modelled results for C:N were in agreement with measured results at most stand ages (Fig. 8c). Values for the ratio of $REMS/REMS_{95\%}$ for total carbon (0.650), total nitrogen (0.727) and C:N (0.559) all indicate a general good fit between modelled and measured data for the mineral soil.

Across a Climatic Gradient

Measured and modelled results for stem biomass carbon across the BFTCS from Candle Lake, Saskatchewan, to

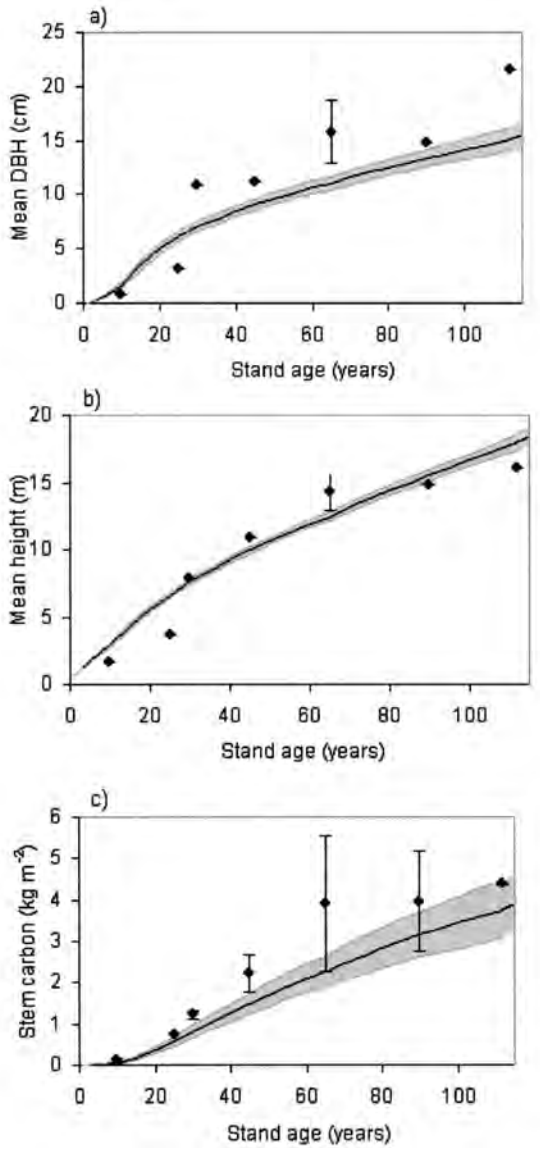

Fig. 5. Comparison of measured and modelled estimates for (a) mean stand DBH, (b) mean stand height and (c) stem biomass carbon, across stand ages at Candle Lake. Error bars show the standard deviation of measured data. Shaded area shows standard deviation of the modelled results.

Thompson, Manitoba, exhibited a similar trend of decreasing stem biomass carbon (Table 6). Although the trend was similar, modelled estimates were lower than measured for the Candle Lake and Flin Flon sites and higher than measured results for the Thompson site.

Measured values for C, N and C:N in the forest floor and mineral soil were similar across all sites. Modelled results also showed no differences between sites, but the model predicted more carbon and therefore higher C:N ratios in the forest floor compared with measured values. Results were comparable between measured and modelled results for the mineral soil (Table 6).

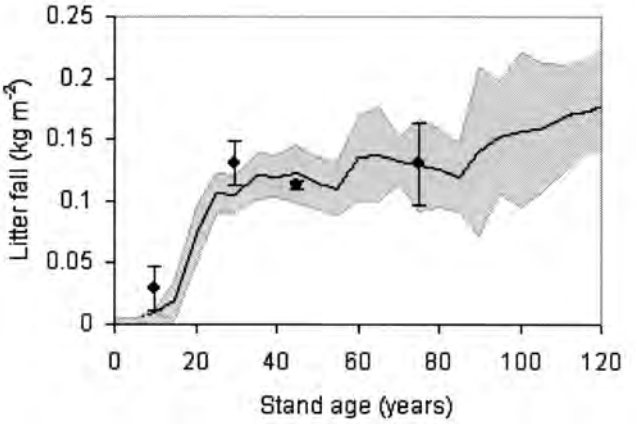

Fig. 6. Comparison of measured and modelled estimates for litterfall across stand ages at Candle Lake. Error bars show the standard deviation of measured data. Shaded area shows standard deviation of the modelled results.

Scenario Testing

Results from the scenarios tested (Table 7) under a current climate indicate that one mid-rotation thinning where all residues remained on the site is the best management practice when only considering the tradeoffs between productivity and carbon stored in the soil. Harvested wood increased by 7.4% with little change in soil carbon stocks. Whenever tree residues were removed from the site forest floor carbon dropped by 10–14%. Presumably some of the logging residues lost to the site would become an addition elsewhere (i.e., road side landing) and therefore the net loss of carbon from the entire system would not be that large. However, it is interesting to note that the model predicted a loss, not only in the forest floor carbon, but also for mineral soil carbon (6–7%) when residues were removed from the site. In both cases where residues were removed productivity was reduced or not affected.

Modelled results suggest that under the projected change in climate (Table 7), harvested wood would increase by about 13% across all scenarios as a result of a warming climate. Only a small increase in loss of carbon from the mineral soil would result from climate warming, but the greatest change would occur as a loss of carbon from the forest floor ranging from an additional 17–21% depending on the harvesting practice. Even under climate warming, the best practice from the scenarios evaluated, based only on the tradeoffs between productivity and carbon retention in soil, is still a mid-rotation thinning with all residues left on the site. This practice resulted in the highest productivity, where carbon accumulated in the tree biomass and losses of carbon from soil were minimized.

DISCUSSION

Individual Tree and Stand Biomass Carbon

Modelled results for changes in tree parameters (diameter, height and stem carbon) over stand age at the Candle Lake site were satisfactory except that the model sometimes underestimated stem carbon by about 0.3–0.9 kg m^{-2}.

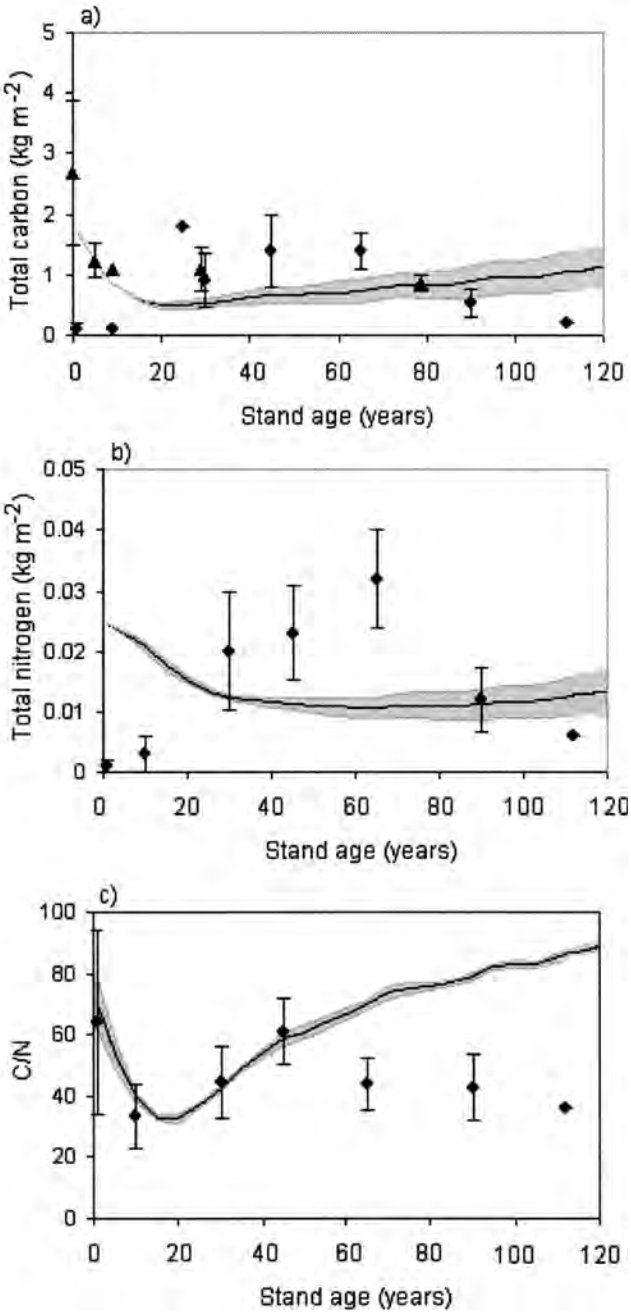

Fig. 7. Comparison of measured and modelled forest floor (a) carbon, (b) nitrogen and (c) C:N across stand ages at Candle Lake (additional values for carbon (identified by triangles) are from Howard et al. (2004)). Error bars show the standard deviation of measured data. Shaded area shows standard deviation of the modelled results.

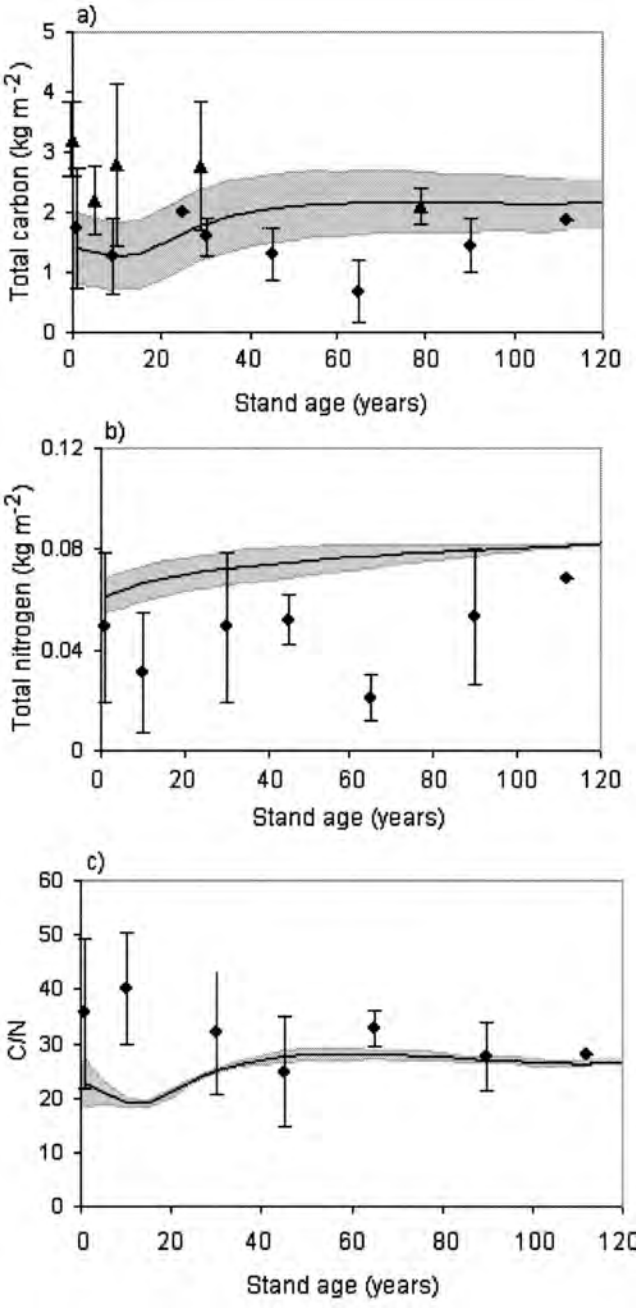

Fig. 8. Comparison of measured and modelled mineral soil (a) carbon, (b) nitrogen and (c) C:N across stand ages at Candle Lake [additional values for carbon (identified by triangles) are from Howard et al. (2004)]. Error bars show the standard deviation of measured data. Shaded area shows standard deviation of the modelled results.

Different equations were used by the model and for the measured data to estimate stem carbon from the height and diameter of individual trees and this may account for some of the observed discrepancies. A comparison of individual tree stem carbon estimated by the different equations, but based on the same tree height and diameter data (n = 10), shows that the estimates can differ by as much as 0.45 kg m^{-2} and if bark is included in the estimate the difference can be as high as 0.7 kg m^{-2} (Fig. 9). The difference between estimates from the different equations is greater for older than younger-aged stands (Fig. 9) and this may partially account for the larger discrepancy between modelled and

Table 6. Comparison of means simulated by the EFIMOD 2 jack pine model and measured along the BFTCS sites (standard deviation shown in parentheses)

		Candle Lake, STOJP		Flin Flon, FJM2		Thompson, NTOJP	
Data		Measured	Simulated	Measured	Simulated	Measured	Simulated
Age (yr)		90	90	74	74	74	74
DBH (cm)		13.9[z]	13.3 (0.81)	11.7 (2.10)	12.1 (0.82)	10.3 (1.73)	11.3 (0.75)
Height (m)		14.2[z]	15.5 (0.43)	13.3 (2.42)	13.7 (0.43)	10.1 (1.74)	13.4 (0.40)
Stem carbon (kg m^{-2})		4.0 (1.2)	3.2 (0.5)	3.4 (0.7)	2.7 (0.5)	1.7 (0.6)	2.3 (0.4)
Forest floor	Carbon (kg m^{-2})	0.53 (0.24)	0.88 (0.20)	0.43 (0.38)	0.90 (0.21)	0.52 (0.44)	0.97 (0.25)
	Nitrogen (kg m^{-2})	0.012 (0.006)	0.011 (0.003)	0.012 (0.007)	0.012 (0.003)	0.012 (0.009)	0.014 (0.003)
	C/N	44 (11)	80 (3)	36 (10)	75 (4)	43 (9)	69 (4)
Mineral soil	Carbon (kg m^{-2})	1.45 (0.46)	2.15 (0.48)	1.89 (0.95)	2.17 (0.71)	1.33 (0.48)	2.16 (0.50)
	Nitrogen (kg m^{-2})	0.053 (0.027)	0.080 (0.020)	0.079 (0.046)	0.077 (0.022)	0.058 (0.015)	0.077 (0.022)
	C/N	27 (6)	27 (1)	24 (7)	28 (1)	23 (12)	28 (1)

[z]No data on standard deviation.

Table 7. Results of EFIMOD 2 jack pine model simulations under current and projected climate warming

		% Change relative to standard scenario		
Climate	Forest management practice	Harvested wood	Forest floor carbon	Mineral soil carbon
Current	Clear cutting 70 yr; all tree residues removed	–5.1	–10	–6
	Thinning 40 yr, clear cutting 70 yr; all tree residues remained	7.4	–2	1
	Thinning 40 yr, clear cutting 70 yr all tree residues removed	0	–16	–7
Projected	Clear cutting 70 yr all tree residues remained	13.7	–21	–1
	Clear cutting 70 yr all tree residues removed	7.5	–27	–7
	Thinning 40 yr, clear cutting 70 yr; all tree residues remained	21.7	–23	–1
	Thinning 40 yr, clear cutting 70 yr; all tree residues removed	13.0	–29	–9

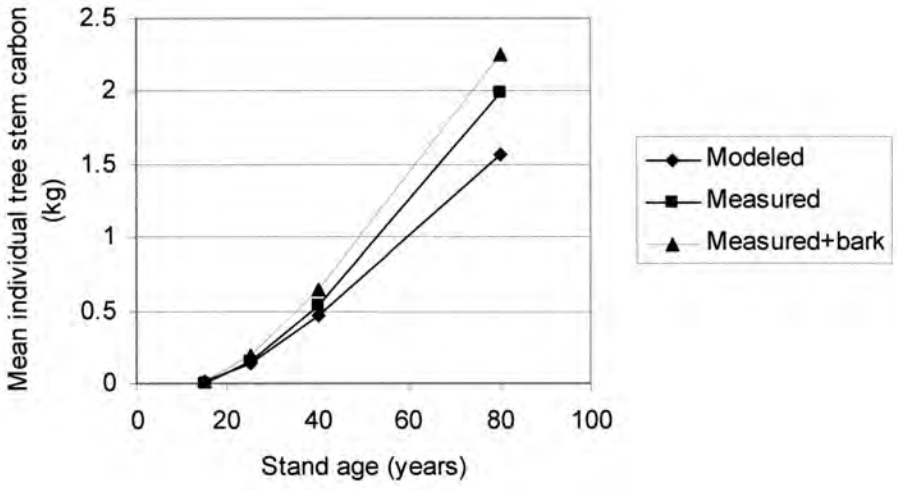

Fig. 9. Individual tree stem carbon estimated by EFIMOD 2 and by equations used along the Boreal Forest Transect Case Study (with and without bark).

measured values at older than younger stand ages (Fig. 5c). Thus, in future applications of the model, modelled and measured estimates can be brought into very close agreement by using the same equations for estimation of tree biomass.

Another reason that modelled and measured stem biomass carbon do not agree exactly may be related to differences in stem density used to estimate stand level biomass carbon. The sites selected to represent the chronosequence at Candle Lake were likely initiated by different types and intensities of disturbance events (fire/harvest practices) that could result in different initial stand densities. Jack pine stands initiated by fire typically have much higher initial stand densities (10–50 000 stems ha^{-1}) and would experience more intense self-thinning in the early stages of stand development than harvested and planted stands (1500–2500

stems ha^{-1}) (Jeglum 1994). However, based on the sensitivity analysis for initial stem density and the subsequent effects of self-thinning, it was found that the model's ability to predict stand level tree biomass carbon over the normal span of stand ages for jack pine (< 80 yr) is not very sensitive to initial stand density (Fig. 3a). At very old stand ages (> 80 yr) the stand biomass carbon predicted by the model becomes more sensitive to initial stand density. An increase in initial stand density from 1000 to 9000 stems ha^{-1} can account for a difference of about 1.0 kg ha^{-1} in tree biomass carbon.

Soil Carbon

In general the correspondence between modelled and measured results for the forest floor and mineral soil carbon was satisfactory. When data from Howard et al. (2004) are combined with data from this paper (Figs. 7a and 8a) modelled results are in agreement with measured results from the various sources up to a stand age of about 65 yr with the exception of the low estimates in the forest floor for young stands (1, 9 yr) measured at the BFTCS.

Discrepancies (i.e., low vs. high forest floor carbon for young-aged stands) that are observed between modelled and measured results for changes in carbon and nitrogen in the forest floor and mineral soil over stand age may be attributed to the highly variable impact of disturbances (natural and anthropogenic) on measured values that are currently not reflected in the model. Discrepancies may also be a result of pools given the same name in the model and in the field, being estimated as the sum of different components. For example, estimates for total carbon and nitrogen in the forest floor from the model are sometimes lower than measured between the stand ages of 25 and 65 yr. This is likely due to the fact that forest floor samples taken in the field included moss, lichens and other ground cover detritus. The model estimates the forest floor from detrital inputs only from trees (needles, branches, wood) but does not, at this time, include contributions from the under story and ground cover vegetation.

Forest floor carbon estimated for young stands from the BFTCS and Howard et al. (2004) (Fig. 7a) are very different and likely reflect the difficulties associated with selecting appropriate sites for a chronosequence (Howard et al. 2004) and the impact of diverse harvesting practices on the quantity of detritus remaining on the site and its spatial distribution both laterally across the site and vertically through admixing with the mineral soil. The resulting heterogeneity of the forest floor creates difficulties for sampling in the field and subsequent estimation and presents a challenge to modellers who must determine initialisation values for the forest floor. In this study the initial value for the forest floor was determined by an average value estimated from data for forest soils (Siltanen et al. 1997) under jack pine in the same ecozone and with the same soil taxonomic classification as the study sites. Presumably this provided an independent estimate from a set of soils where the forest floor originated from a variety of pre-disturbance histories and stand ages, even if they are unknown. This proved to be a satisfactory approach as the independently estimated value falls midway between the estimates of Howard et al. (2004) and the BFTCS and produced modelled results that are comparable with the measured results over the stand ages.

Although insufficient data are available at this time to be conclusive, it is of interest to note that measured data along the BFTCS follow a trend consistent with normal stand development up to an age of about 65 yr. This is around the stand age for maximum mean annual increment for jack pine (Leiffers et al. 2003) and is around historical fire return interval in jack pine forests (Bergeron 1991). It is interesting to note that for stands present along the BFTCS that are much older than 65 yr, forest floor carbon declines to an age of 112 yr (Fig. 7a) and mineral soil carbon increases over the same span in stand ages (Fig. 8a). This suggests that for jack pine in a stable environment (i.e., the absence of natural disturbance from fire) soil carbon may transfer from the forest floor to the mineral soil where it becomes stabilized.

Trends Across a Climatic Gradient

A comparison of measured and modelled results across the climatic gradient for tree biomass carbon, forest floor C and N and mineral soil C and N shows that the model was able to reflect trends similar to those resulting from the measured data (Table 6). Tree biomass carbon decreased from Candle Lake at the southern limit of the boreal forest where the climate is warm and dry up to Thompson where the climate is wetter and colder than at Candle Lake. Soil carbon and nitrogen stocks in the forest floor and mineral soil did not change in response to a change in climate. Although the model was able to reflect the trends for tree biomass carbon it did not express as wide a range in values compared with the measured estimates. Measured estimates range from 4.0 in Candle Lake to 1.7 kg m^{-2} in Thompson, while modelled estimates range from 3.2 to 2.2 kg m^{-2} for the same sites (Table 6). Some of this difference may have resulted from the different biomass equations used in the model and for the measured data (previously discussed, Fig. 9). The model also overestimated total carbon and therefore C:N ratios in the forest floor at all sites.

Scenario Testing

Preliminary results from the scenario testing suggest that under the existing climate both productivity and soil carbon stocks are best maintained by retaining residues from harvesting on site. The results further suggest that productivity may be enhanced by a mid-rotation thinning with little change to soil carbon stocks as long as residues remain on the site. Scenario testing results also suggest that under a warming climate carbon will always be lost from soil organic matter, but to minimize the loss, especially from the mineral soil, residues should be left on site. Increased productivity after the mid-rotation thinning in the scenario testing is consistent with results from research on radiata pine (*Pinus radiata* D. Don) in Australia where Carlyle (1994) demonstrated the advantages to tree growth on sandy soils of using a mid-rotation thinning where residues were retained on site. This practice favoured N retention because nitrogen was released from the decomposing residues at a

rate slow enough to be taken up by the remaining trees with no loss of nitrogen due to leaching.

Calibration and Validation Issues

One of the challenges for calibration of the model was estimating the parameters of NPP reallocation and N retention in needles prior to abscission because there is little relevant published data for jack pine. The model is currently sensitive to these parameters, but as more data becomes available for jack pine, model simulations will improve and the model's sensitivity reduced.

Another challenge presented for establishing both initial values and summary validation data sets was ensuring that simulated and measured pools represented, as far as it is possible, the same ecosystem components. This applied to both above-ground (tree) and below-ground (forest floor and mineral soil) pools.

Although EFIMOD 2 is capable of simulating complex stand structure development, the jack pine simulations presented in this paper represent the simplest type of stand development; one cohort over time. Thus, particular care had to be taken to ensure that the validation data also represent a single cohort. Data had to be carefully evaluated so that mean stand diameter, mean stand height and stand biomass carbon were calculated from trees representative of a single cohort.

Qualitative differences existed between what was measured as the forest floor at the validation sites and what is simulated as the forest floor in the model. The model includes needle litter, branch litter and wood as detrital inputs to the forest floor but at the validation sites significant quantities of lichens, mosses and understory detritus were included in the forest floor measurements. These differences had to be factored into the interpretation when comparing results for the forest floor from the model and data from the validation sites. Future model development for EFIMOD 2 will include the capability to include the contribution of understory and ground cover vegetation to forest ecosystem dynamics.

EFIMOD 2 models mineral soil carbon based on a depth of 100 cm, but in order to make the pools comparable we used a variable depth of mineral soil for estimation of carbon and nitrogen based on the detection limit for carbon in the mineral soil. This is because C:N in the mineral soil is an important parameter for the simulation of soil carbon and nitrogen dynamics in EFIMOD 2. In the sandy-textured Brunisolic soils at the validation sites soil nitrogen could be detected to a lower limit than carbon. Results from the analyses of some samples where nitrogen could be detected but little carbon detected produced unrealistically low estimates for C:N ratios. Therefore, to ensure that modelled and measure pools were compatible mineral soil carbon and nitrogen were both estimated to the depth where carbon could be reliably analyzed.

Simulated and measured results were in relatively good agreement but some discrepancies between the two likely can be attributed to the effects of disturbances on measured stand and soil pools that are not currently reflected in the model. The history of disturbances at sites used for model validation, like those used in this study, is typically poorly documented or unknown, yet it is well understood that disturbances from fire, harvesting, insects and wind can have profound and highly variable effects on stand structure and stand dynamics that determine detrital inputs to the soil system. These effects leave their imprint on the carbon and nitrogen stocks in the forest floor and in the mineral soil. Future model development for EFIMOD 2 will include integration of the effects of anthropogenic and natural disturbances on forest ecosystem dynamics.

CONCLUSION

EFIMOD 2 was successfully calibrated for jack pine from data published in the literature and validated using data collected along the BFTCS. Simulated and measured data agreed best for stand development between 20 and 65 yr of age. The model was able to reproduce trends in response to a climatic gradient similar to those observed for the measured data. The model was able to reflect carbon and nitrogen dynamics and has the potential to simulate nitrogen feedbacks on carbon dynamics in response to forest management practices and climate change in the absence of natural disturbances. Challenges for modelling this jack pine ecosystem included arriving at reliable estimates for NPP reallocation and N retention in needles before abscission, and ensuring the qualitative nature of measured and modelled pools were comparable.

Preliminary scenario testing of EFIMOD 2 for jack pine showed that different forest harvesting strategies, under the present and projected change in climate, influence feedback mechanisms between trees, the forest floor and the mineral soil. These results indicate that EFIMOD 2 can be successfully adapted to jack pine in Canada and has the potential to assess more complex scenarios for the interactions between climate change and management that reflect the feedbacks between soil and trees. Natural and anthropogenic disturbance effects were not assessed in the scenario testing because they were not reflected in the version of the model used when this research was done. Recently a new version of EFIMOD II was developed that includes disturbance effects and it is currently being tested.

ACKNOWLEDGEMENTS

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