Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin II: model evaluation

M.T. Moroni, C.H. Shaw, W.A. Kurz, and G.J. Rampley

Abstract: The Intergovernmental Panel on Climate Change recommends that countries that use advanced (Tier 3) models to meet their international reporting obligations on forest greenhouse gas emissions and removals evaluate model predictions against independent field data. Unfortunately, estimates of total ecosystem C stocks and stock changes are scarce and consequently the recommended evaluations are rarely completed. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is the core model of Canada's National Forest Carbon Monitoring, Accounting, and Reporting System that implements an Intergovernmental Panel on Climate Change Tier 3 approach. It accounts for biomass, dead organic matter, and soil C pools as affected by natural and anthropogenic disturbances. We used data from a recent study of total ecosystem C stocks for black spruce (*Picea mariana* (Mill.) BSP) and balsam fir (*Abies balsamea* (L.) Mill.) boreal forest chronosequences of different disturbance origins in Newfoundland, Canada, to evaluate C stock and stock change predictions from the CBM-CFS3. Results indicated that the accuracy of the CBM-CFS3 is high for landscape-scale estimation of C stocks. Comparison of estimates stratified by lead species or disturbance type indicated that model accuracy could be improved at finer scales by increasing specific model parameters such as the snag fall rate and woody debris decay rates relative to default parameters.

Résumé : Le Groupe d'experts intergouvernemental sur l'évolution du climat recommande que les pays qui utilisent des modèles avancés (niveau 3), pour s'acquitter de leurs engagements internationaux en matière de présentation de rapports sur les émissions et l'élimination des gaz à effet de serre par les forêts, évaluent les prédictions des modèles à partir de données terrain indépendantes. Malheureusement, les estimations des stocks totaux de C des écosystèmes et des variations de ces stocks sont peu fréquentes et les évaluations recommandées sont par conséquent rarement effectuées. Le modèle du bilan du carbone du secteur forestier canadien (MBC-SFC3), qui utilise une approche de niveau 3 telle que définie par le Groupe d'experts intergouvernemental sur l'évolution du climat, est au cœur du Système national de surveillance, de comptabilisation et de production de rapports concernant le C des forêts du Canada. Cette approche tient compte de la biomasse, de la matière organique morte, des réservoirs de C dans le sol et de la façon dont ils sont influencés par les perturbations d'origine naturelle et anthropique. Nous avons utilisé des données provenant d'une étude récente des stocks totaux de C de l'écosystème réalisée dans des chronoséquences de forêt boréale composée d'épinette noire (*Picea mariana* (Mill.) BSP) et de sapin baumier (*Abies balsamea* (L.) Mill.) issues de différentes perturbations à Terre-Neuve, au Canada, pour évaluer les prédictions du modèle MBC-SFC3 concernant les stocks de C et ses variations. Les résultats indiquent que le modèle MBC-SFC3 a une grande précision pour estimer les stocks de C à l'échelle du paysage. La comparaison des estimations stratifiées sur la base des principales espèces ou des types de perturbation indique que la précision du modèle peut être améliorée en développant certains paramètres du modèle tels que les taux de renversement des chicots et de décomposition des débris ligneux relativement aux paramètres implicites.

[Traduit par la Rédaction]

Introduction

Canada's forest is important to the global C cycle and many forest ecosystem models are being adapted or developed to quantify its C dynamics (e.g., Kurz and Apps 1999; Chen et al. 2000; Chertov et al. 2009; Kurz et al. 2009). As a signatory to the United Nations Framework Convention on Climate Change (2009), Canada provides annual reports on emissions and removals of CO_2 and non-CO_2 greenhouse gases in the managed forest. The Carbon Budget Model of

Received 23 November 2009. Accepted 29 July 2010. Published on the NRC Research Press Web site at cjfr.nrc.ca on 20 October 2010.

M.T. Moroni.[1,2] Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre, P.O. Box 960, Corner Brook, NL A2H 6J3, Canada.
C.H. Shaw. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB T6H 3S5, Canada.
W.A. Kurz and G.J. Rampley. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada.

[1] Corresponding author (e-mail: martin.moroni@forestrytas.com.au).
[2] Present address: Forestry Tasmania, 79 Melville Street, Hobart, Tasmania 7050, Australia.

doi:10.1139/X10-155

the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2009) is the core model of Canada's National Forest Carbon Monitoring, Accounting, and Reporting System (Kurz and Apps 2006). The model implements a Tier 3 approach of the Intergovernmental Panel on Climate Change (IPCC) for reporting C stocks and stock changes (IPCC 2003, 2006). The CBM-CFS3 is a stand- and landscape-scale forest C accounting framework that simulates the impacts of anthropogenic and natural disturbances — including harvesting, insect outbreaks, and fire — on forest C stocks (Kurz et al. 1992, 2009; Kurz and Apps 1999). To meet the requirements of an operational-scale forest C budget model (Kurz et al. 2002), the Canadian Forest Service developed a toolbox that includes the scientific model, a graphical user interface, data pre- and postprocessing tools, and a detailed user's guide (Kull et al. 2007).[3] The 2006 IPCC Guidance for National Greenhouse Gas Inventories recommends models used for reporting be evaluated against field data collected independent of calibration (IPCC 2006). The IPCC further recommends that the representation of dead organic matter (DOM) and soil C dynamics in Tier 3 models be linked to the biomass dynamics of the stand. Knowledge of the time since disturbance and the type of last disturbance will reduce uncertainties in the estimates of stock changes in DOM and soil C pools. Unfortunately, data comparing the effect of natural and anthropogenic disturbance history on forest C stocks, in particular DOM and soil C, are limited. Therefore, data need to be collected to support the development of forest management strategies aimed at decreasing C sources and increasing C sinks (Canadell et al. 2007) and to validate tools such as the CBM-CFS3 and their estimates of C stocks in forests of differing disturbance at origin and at various times following disturbance.

The recent and comprehensive work of Moroni (2006) and Moroni et al. (2010) provides such a unique data set and opportunity to assess the performance of the CBM-CFS3 in black spruce (*Picea mariana* (Mill.) BSP) and balsam fir (*Abies balsamea* (L.) Mill.) boreal forests and identify components of the CBM-CFS3 that could potentially be improved to increase the model's accuracy when applied to these and similar ecosystems. The geographic range of balsam fir extends from Alberta to the Atlantic coast and includes many of the northeastern US states. Black spruce ranges in a broad band from northern Massachusetts and northern Labrador in the east, west to the Alaskan coast (Burns and Honkala 1990). In addition, many aspects of these forests, especially live tree and dead wood dynamics, are comparable with forests, in particular coniferous forests, of a similar diameter (Harmon et al. 2004; Hagemann et al. 2009; Smith et al. 2009). Small-diameter forests — especially coniferous ones — comparable with balsam fir and black spruce occur over an enormous area in the circumpolar boreal (Ahti et al. 1968; Hämet-Ahti et al. 1974; Ecoregions Working Group 1989) as well as in cooler, higher-elevation regions south of the boreal (Clark et al. 1998; Zielonka and Niklasson 2001). Therefore, the data of Moroni (2006) and Moroni et al. (2010) have the potential to not only contribute to improving model accuracy in Newfoundland but also to provide insights into modeling black spruce and balsam fir forests in other parts of North America and similar forests around the world.

These data are ideal for comparison with the CBM-CFS3 for three main reasons. First, the study design focused on two species (black spruce and balsam fir) of major economic and ecological significance in the boreal forests of Canada. Second, it assessed impacts of four dominant forest disturbance types in Newfoundland: harvest (H), harvest with precommercial thinning (HT), burned (B), and insect killed (I) (Moroni et al. 2010). Third, the very detailed sampling design enabled mapping of most CBM-CFS3 pools to measured data. Thus, the objectives of the research reported here were to (*i*) compare field-measured C stocks with those predicted using the CBM-CFS3 with emphasis on (*a*) the impact of different stand-replacing disturbance types on forest C stocks and (*b*) changes in forest C pools with time since disturbance and (*ii*) identify model assumptions that could potentially be modified to more accurately reflect C dynamics of these forest ecosystems.

Methods

We provide a brief overview of the field study and the CBM-CFS3 including the modeling assumptions specified for the simulation of the field study sites. We also describe the statistical methods used to evaluate model performance. Readers are referred to Kurz et al. (2009) for a detailed description of the model and to Moroni et al. (2010) for a detailed description of the field study and sampling design.

Overview of the field study

The field study was conducted in Newfoundland (Moroni 2006; Moroni et al. 2010) to characterize forest C stocks of short-lived small-diameter black spruce and balsam fir boreal forests regrown following natural and anthropogenic disturbances over the course of stand development and to provide a data set to allow the evaluation of the CBM-CFS3 estimates for these systems. Sites were selected to represent 12 populations, hereafter strata, that dominate the Newfoundland boreal forest defined by the combination of dominant tree species (black spruce (S) or balsam fir (F)), a disturbance type (H, HT, B, I, or unknown origin (U)), and a stand age (young (Y), middle-aged (M), or old (O)) (Tables 1 and 2). Half of the strata were in fir and half in spruce forests. Three sampling sites were located for each stratum for a total of 36 sites. The 12 strata were grouped to produce four chronosequences (Table 1) and a paired comparison of precommercially thinned and unthinned balsam fir. Four sample plots (total number of plots = 144) were located at each sampling site. The original field data were summarized according to the pool definitions used for the CBM-CFS3 (Table 3).

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

Overview

The CBM-CFS3 is a stand- and landscape-level model of forest dynamics that tracks C stocks, stock changes, and emissions and removals of CO_2, CH_4, and CO (Kurz et al.

---

[3] The model and documentation are available from carbon.cfs.nrcan.gc.ca.

Table 1. Annotations used to describe strata and chronosequences of Newfoundland balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*) sites.

Annotation	Description
Species	
F	Balsam fir
S	Black spruce
Disturbance history	
H	Harvested
HT	Harvested and thinned
B	Burned (wildfire)
I	Insect
U	Unknown
Age class	
Y	Young
M	Medium
O	Old
Strata chronosequences	
F/I/Y–F/I/M–F/U/O	Balsam fir stands of insect origin that are young and medium aged plus old-aged stands of unknown origin
F/H/Y–(F/H/M or F/HT/M)–F/U/O	Balsam fir stands of harvested origin that are young and medium aged plus harvested and thinned medium-aged stands plus old-aged stands of unknown origin
S/H/Y–S/H/M–S/H/O	Black spruce stands of harvested origin that are young, medium, and old aged
S/B/Y–S/B/M–S/B/O	Black spruce stands of fire origin that are young, medium, and old aged

1992; Kurz and Apps 1999). The CBM-CFS3 (version 1.0) used in this analysis is a substantially advanced version of the model that, among other changes, includes a more detailed presentation of DOM dynamics (Kurz et al. 2009).

Biomass C dynamics in the CBM-CFS3 are simulated in annual time steps using yield curves (defining merchantable volume as a function of stand age) that are provided by the user. Merchantable volume is converted into aboveground biomass components based on equations used in Canada's National Biomass Inventory (Boudewyn et al. 2007). Belowground biomass is predicted from aboveground biomass using stand-level regression equations for softwood and hardwood species that relate root biomass to aboveground biomass (Li et al. 2003).

To improve the representation of C dynamics in dead standing trees, four additional C pools have been added to the earlier version of the model (Kurz and Apps 1999). These contain standing dead stemwood (snags) and the dead branches associated with standing dead trees for the softwood and the hardwood stand components (Kurz et al. 2009). Moreover, to facilitate comparison between modeled and measured DOM and soil C pools, the model's DOM pools have been partitioned into above- and belowground components (along the interface between the forest floor and the mineral soil).

Decomposition for every DOM pool is modeled using a temperature-dependent decay rate that determines the amount of organic matter that decomposes in a DOM pool every year. The CBM-CFS3 uses proportions to determine the amount of C in the decayed material that is released to the atmosphere (P_{atm}) or transferred to the more stable slow DOM pools (P_{t}) (Table 4). Decay dynamics are simulated in each annual time step. Applied decay rates (ADR) in the model runs for this study were calculated for each DOM pool as

$$[1]\qquad \mathrm{ADR} = \mathrm{BDR} \times \mathrm{TempMod}$$

where ADR is the applied decay rate (year^{-1}), BDR is the base decay rate (year^{-1}) at a reference mean annual temperature of 10 °C, and TempMod is a temperature modifier (Kurz and Apps 1999). The temperature modifier (TempMod) reduces the decay rate for mean annual temperatures below the reference temperature and is calculated as

$$[2]\qquad \mathrm{TempMod} = \mathrm{e}^{[(\mathrm{MAT}-\mathrm{RefTemp})\times\ln(Q_{10})\times 0.1]}$$

where MAT is the mean annual temperature, RefTemp is the reference mean annual temperature of 10 °C, and Q_{10} is a temperature sensitivity coefficient (Table 4).

As in the earlier versions of the model, each biomass component can be transferred to DOM pools through litterfall, tree mortality, and disturbance impacts. Litterfall and other turnover rates for each biomass pool are defined by regional parameter sets. Annual biomass turnover rates are used to represent mortality that occurs for most stand development to the point of stand breakup. When the merchantable volume over age curve indicates declining volume at higher stand ages (stand breakup), mortality is the sum of biomass loss (declining volume) plus annual turnover.

Disturbance impacts of each disturbance type are quantified through a disturbance matrix (Kurz et al. 1992) that defines the proportion of C transferred between biomass and DOM pools at the time of the disturbance. A unique disturbance matrix for each disturbance type is used in the annual time step of the disturbance to transfer proportions of C from predisturbance to postdisturbance pools, including transfers out of the ecosystem to the forest product sector and to the atmosphere. Disturbance matrices affect the quantity and composition of ecosystem C pools remaining after disturbance, e.g., combustion of the forest floor in a wildfire or transfer of stemwood out of the forest during harvest. In this study, three regional default disturbance matrices were used, stand-replacing wildfire, clearcut-harvesting, and insect disturbances, and two modified disturbance matrices that are described in the next section (Assumptions). The default stand-replacing fire and modified harvesting disturbance matrices are shown in Table 5 to illustrate how very different disturbance impacts are implemented in the model and in this study. At the time of a stand-replacing wildfire, all softwood and hardwood merchantable stemwood is transferred to the snag stemwood pools (proportions = 1) whereas in the non-stand-replacing harvest, a small proportion of the softwood merchantable stemwood is transferred to coarse woody debris (CWD) (medium pool) and the majority is transferred to harvested wood products (products pool); the hardwood merchantable stemwood stays as hardwood merchantable stemwood (proportion = 1) because it is not harvested in black spruce and balsam fir dominated stands in Newfoundland. The wildfire disturbance matrix is more complex than the harvest disturbance matrix because vary-

Table 2. Range of values for the characteristics of Newfoundland balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*) sites studied (taken from Moroni et al. 2010).

Lead species/ disturbance history/ stand age class[a]	Years of last disturbance[b]	Current forest type[a,c]	Current forest age (years)[b,d]	Previous forest type[c,e]	Previous forest age (years) when disturbed[d,f]	Mean annual temperature (°C)[e,g]	Precipitation (mm·year^{-1})[e,g]	Elevation (m)
Balsam fir								
F/I/Y	2000–2001	na	na	bf 2 M	60–66	1.7	1103–1104	45
F/I/M	1966–1971	bf 2 M–G	30	bf 1–2 M	96–136	4.2–4.4	1380–1393	65
F/H/Y	2002–2003	na	na	bf 1–2 M	60–95	2.8–3.0	1112–1318	255–325
F/H/M	1962–1971[g,h]	bf 2 M–G	32–36	bf 2 M	102–111	3.3–3.9	1023–1479	105–280
F/HT/M[i]	1962–1971[g,h]	bf 1–2 M–G	32–36	bf 2 M	102–111	3.3–3.9	1023–1479	105–280
F/U/O	1894–1917	bf 2 G	86–109	na	na	2.6–2.7	1437–1468	435–445
Black spruce								
S/B/Y	2002–2004	na	na	bs 2 M	62–75	3.3–3.4	1122–1211	145–217
S/B/M	1970	bs 2–3 M	31	bs 1 M	76	3.3	1215–1217	219–231
S/B/O	1930s[g,h]	bs 1–2 M	68–92	na	na	3.2–3.3	1151–1279	99–194
S/H/Y	2001–2002	na	na	bs 1–3 M–G	71–72	3.3	1139–1143	60–99
S/H/M	1965–1970	bsbf 1–2 M	31–36	bsbf 2–3 P–M	85–136	3.4	1127–1197	175–248
S/H/O	1930s[g,h]	bs 2–3 M	63–72	na	na	3.3	1150–1158	99–108

Note: na, data not available or applicable.

[a] Lead species: black spruce (S), balsam fir (F); disturbance history: insect killed (I), harvested (H), harvested with precommercial thinning (HT), origin unknown (U); stand age class: young aged (Y), middle aged (M), old aged (O).

[b] Stand age was substituted for year of disturbance in old-aged stands where disturbance origin is not known.

[c] Newfoundland forest inventory of current forest; forest inventory (ab A B) where bf = >75% balsam fir, bs = >75% black spruce, bsbf = 50%–75% black spruce, 25%–50% balsam fir. A = crown density where 1 is over 75% crown closure, 2 is 51%–75% crown closure, and 3 is 26%–50% crown closure; B is site class (for merchantable yield) where M is medium and G is good. Growth and yield curves for a site type on the northern peninsula are slightly lower than for the same site type in central western Newfoundland (Newfoundland and Labrador Department of Natural Resources. 2005. Unpublished Newfoundland forest growth curves).

[d] Forest age at measurement or age of forest disturbed within 3 years of measurement. Forest ages determined from increment bore or stump ring count.

[e] Newfoundland forest inventory for forests disturbed within 3 years of measurement. Aerial photographs were typed to determine previous forests in stands disturbed >3 years of measurement.

[f] Forest age was determined from increment bore or stump ring count where forests were disturbed within 3 years of measurement. Previous forest ages in sites disturbed >3 years before measurement were estimated from aerial photographs.

[g] Averages for the period 1971–2000 using estimates of McKenney et al. (2001).

[h] The exact year of disturbance is unavailable for some sites.

[i] Age when thinned 14–20 years.

Table 3. Mapping of measured ecosystem C pools to those of the CBM-CFS3.

Ecosystem C pool	CBM-CFS3 C pools[a]	Measured C pools[b]
Live trees		
SW_{Abio}	SW merchantable + other + foliage	SW stemwood, branches,bark, and foliage (all diameter at breast height (DBH))
SW_{roots}	SW fine + coarse roots	SW roots
HW_{Abio}	HW merchantable + other + foliage	HW stemwood, branches,bark, and foliage (all DBH)
HW_{roots}	HW fine + coarse roots	HW roots
Dead organic matter		
Snag stems	Snag stems	≥9 cm DBH snag stems
Snag branches	Snag branches	<9 cm DBH snags + ≥9 cm DBH snag branches and top + stumps
CWD	Medium	>10 cm woody debris + buried wood
S&FWD	AG fast excluding coarse root component	≤10 cm woody debris
Dead coarse roots	BG fast + coarse root component of AG fast	Dead coarse roots (not measured)
Soil		
Organic horizons	AG very fast + AG slow	L, F, H + O[c] soil horizons including dead fine roots
Mineral horizons	BG very fast + slow	Mineral soil to 45 cm depth including dead fine roots

Note: The CBM-CFS3 does not simulate nonwoody vegetation or shrubs. SW, softwood; HW, hardwood; Abio, aboveground biomass; CWD, coarse woody debris; S&FWD, small and fine woody debris; AG, aboveground; BG, belowground.

[a] For a detailed description of the CBM-CFS3 pool, see Kurz et al. (2009).

[b] Original data taken from Moroni (2006) and Moroni et al. (2010).

[c] Soil Classification Working Group (1998).

ing proportions of foliage and DOM pools are combusted and released into the atmosphere as greenhouse gases (CO_2, CH_4, and CO) or transferred in varying proportion to other DOM pools (Table 5).

Assumptions

All CBM-CFS3 runs have two major components: initialization representing long-term historical stand dynamics that are used to estimate initial DOM and soil pools (see subsequent section) and the simulations that represent stand dynamics from the initial stand age to the end of the simulation period. The CBM-CFS3 was designed as a highly flexible, user-friendly framework that allows users to replace default assumptions with site-specific parameters and scenario assumptions. These assumptions can be applied to either or both of the initialization and simulation components.

In this study, only default parameters for transfer between pools and decomposition during normal stand dynamics were used for the default runs, but some default assumptions were revised to better represent the sites. The first assumption (applied to both initialization and simulations) was to use site average mean annual temperature (MAT) for the period 1970–2001 estimated by McKenney et al. (2001) instead of the single default value of 3.4 °C provided for the entire Boreal Shield East terrestrial ecozone. Secondly, disturbances were assumed to be stand replacing, for initialization and simulations, except that the simulations for recently disturbed sites (within 3 years of measurement) used modified disturbance matrices. Changes to the default disturbance matrices were implemented to capture disturbance-related C dynamics associated with recent harvest and insect disturbances. In the most recent harvests, all hardwoods were left standing, and after the most recent insect disturbance, all hardwoods and 9% of softwoods were left standing. Western Newfoundland fir forests typically contain 9% spruce, which is not defoliated by hemlock looper (*Lambdina fiscellaria* (Guenée)). Thirdly, for each forest type, merchantable yield curves comprising the data for merchantable volume over age for the softwood and hardwood components were selected from yield curves provided by the Newfoundland and Labrador Department of Natural Resources (2005. Unpublished Newfoundland forest growth curves) that are assigned to forest polygons based on characteristics observed from aerial photographs. Site data on species, site class, age, type of last disturbance, and other classifiers were used to confirm the selection of appropriate yield curves for each of the 36 sites (Table 2). Differences in stand growth after the last stand-replacing disturbance, if known, were simulated by transitioning the stand from the yield curve for the predisturbance stand type, used during initialization, to the yield curve for the postdisturbance stand type (Table 2) for the simulations. Where the stand age was less than the time since the last stand-replacing disturbance, a transition rule was applied in the model to incorporate a regeneration delay equal to this difference. Where the previous rotation length is unknown, the final 75-year rotation from the initialization was assumed to be the previous rotation.

Initialization

The CBM-CFS3 uses a spin-up procedure (Kurz et al. 2009) to estimate the quantity of C in soil and DOM pools before simulating scenarios. It requires user-specified assumptions about historic disturbance return intervals, the types of disturbances occurring during the spin-up procedure, and the type of the last disturbance that preceded the establishment of the current stand. To initialize the DOM and soil pools for the simulations in this study, we assumed a 75-year historic disturbance return interval where the historical disturbance type was assumed to be stand-replacing insect outbreak in fir and stand-replacing fire in spruce stands. Stands were assumed to follow growth curves for previous rotation forest types where known and for current

Table 4. Parameters used to simulate dead organic matter dynamics in CBM-CFS3 (modified from Kurz et al. 2009).

	Decay parameters					Physical transfer parameters	
CBM-CFS3 pool	Base decay rate (year^{-1})	Q_{10}	P_{atm}	P_{t}	Pool receiving P_{t}	Transfer rate (year^{-1})	Pool receiving transfer
Snag stems	0.0187	2	0.83	0.17	AG slow	0.032 **(0.10)**	Medium
Snag branches	0.0718	2	0.83	0.17	AG slow	0.10 **(0.20)**	AG fast
Medium	0.0374 **(0.06)**	2	0.83	0.17	AG slow	na	na
AG fast	0.1435 **(0.28)**	2	0.83	0.17	AG slow	na	na
AG very fast	0.355	2.65	0.815	0.185	AG slow	na	na
AG slow	0.015	2.65	1.0	0.0	na	0.006	BG slow
BG fast	0.1435	2	0.83	0.17	BG slow	na	na
BG very fast	0.5	2	0.83	0.17	BG slow	na	na
BG slow	0.0033	1	1.0	0.0	na	na	na

Note: Decomposition parameters include the base decay rate at a reference temperature of 10 °C, sensitivity to temperature (Q_{10}), and the proportion of decay C released to the atmosphere (P_{atm}) versus transferred to a slow dead organic matter pool (P_{t}), where $P_{\mathrm{atm}} + P_{\mathrm{t}} = 1$. AG, aboveground; BG, belowground; na, not applicable. Alternative parameter set shown in parentheses in bold.

rotation forest type where the previous rotation forest type was not known (Table 2).

During the spin-up procedure, stands were grown to the age of the disturbance return interval (75 years) and disturbed using the stand's historic disturbance type. At the end of each disturbance return interval, the CBM-CFS3 compares the slow pool DOM-C (soil) stocks between the current and previous rotations. If the difference in the stocks is <0.1%, then the slow pool DOM C stocks are assumed to be in a quasi-equilibrium state determined by inputs (which are a function of net primary productivity, site productivity, disturbance type, and species) and losses from decomposition (rates are a function of MAT) and disturbances (direct DOM pool losses only from wildfires). Once this equilibrium is reached, the CBM-CFS3 simulates the last rotation(s) with the known disturbance history.

Simulations

Model runs were conducted for each of the 36 sites using the previously described assumptions for initialization and simulations. Two sets of model runs were conducted: the first uses the model's default parameters for the Boreal Shield East terrestrial ecozone in Newfoundland (Table 4) and the second tests if model estimates could be improved by revising parameters for those pools for which modeled and measured values were not in good agreement. Several alternative parameter values for snag and snag branch fall rates and aboveground fast and medium pool base decay rates were evaluated. Results are reported only for the alternative parameter set that provided the best fit (Table 4). Rationale for some of the alternative parameter choices is provided in the Discussion section.

Statistical analyses

Three goodness-of-fit (GOF) statistics (Whitmore 1991; Smith et al. 1997; Smith and Smith 2007) were used to evaluate the accuracy of modeled estimates for each CBM-CFS3 pool mapped to measured estimates. Because replicate measured data were available, we were able to calculate the lack-of-fit (LOFIT) statistic to evaluate the difference between estimates from the model and from measurements made in the field that exclude variations due to field measurement:

$$[3] \qquad \mathrm{LOFIT} = \sum_{i=1}^{n} m_i (O_i - P_i)^2$$

where m_i is the number of replicates of the ith measurement, O_i is the mean value of the ith measurement, P_i is the ith simulated value, and n is the number of simulated and measured pairs being compared. To determine its significance, the LOFIT F value was calculated and compared with the critical $F_{(p=0.05)}$:

$$[4] \qquad F = \frac{\sum_{i=1}^{n}(m_i - 1) \times \mathrm{LOFIT}}{n \sum_{i=1}^{n} \sum_{j=1}^{m_i} [(O_{ij} - P_i) - (O_i - P_i)]^2}$$

where m_i is the number of replicates of the ith measurement, O_i is the mean value of the ith measurement, P_i is the ith simulated value, n is the number of simulated and measured pairs being compared, and O_{ij} is the jth replicate of the ith measurement.

The lack of fit between modeled and measured values was considered not significant if the LOFIT F value was less than the critical F. These statistics can only be calculated accurately from the primary replicate data and cannot be estimated from means and standard errors (Smith and Smith 2007). The percent relative error (E) was calculated to assess model bias. The bias was considered significant if $E > E_{(95\%)}$ or if E was greater than an acceptable standard of 50% (Smith and Smith 2007). Finally, r (correlation) was calculated to assess the degree of association between modeled and measured estimates. The correlation was considered significant if the F value for r was greater than the critical $F_{(p=0.05)}$. The three GOF statistics were calculated for all strata grouped together, grouped by dominant species (black spruce or balsam fir), and grouped by disturbance type (natural or harvested). There were insufficient sites to warrant calculation of GOF statistics for the species by disturbance type interaction.

In cases where the three GOF statistics indicated a significant error (LOFIT) or bias (E), several alternative model parameters were tested to determine if modeled estimates could be improved with minimal adjustment. Once parame-

Table 5. Examples of disturbance matrices used to simulate a stand-replacing wildfire (default) and non-stand-replacing harvest (modified from default disturbance matrix for clearcut harvesting) showing the proportion of C transferred from one CBM-CFS3 pool to another in response to disturbance.

Stand-replacing wildfire			Non-stand-replacing harvest		
From	To	Proportion	From	To	Proportion
SW merchantable	SW stem snag	1	SW merchantable	Medium	0.1365
SW foliage	CO_2	0.9	SW merchantable	Products	0.8635
SW foliage	CH_4	0.01	SW foliage	AG very fast	1
SW foliage	CO	0.09	SW others	AG fast	1
SW others	SW branch snag	0.750002	SW submerchantable	AG fast	1
SW others	CO_2	0.224998	SW coarse roots	AG fast	0.5
SW others	CH_4	0.0025	SW coarse roots	BG fast	0.5
SW others	CO	0.0225	SW fine roots	AG very fast	0.5
SW submerchantable	SW branch snag	0.75	SW fine roots	BG very fast	0.5
SW submerchantable	CO_2	0.225	HW merchantable	HW merchantable	1
SW submerchantable	CH_4	0.0025	HW foliage	HW foliage	1
SW submerchantable	CO	0.0225	HW other	HW other	1
SW coarse roots	AG fast	0.5	HW submerchantable	HW submerchantable	1
SW coarse roots	BG fast	0.5	HW coarse roots	HW coarse roots	1
SW fine roots	AG very fast	0.454948	HW fine roots	HW fine roots	1
SW fine roots	BG very fast	0.5	AG very fast	AG very fast	1
SW fine roots	CO_2	0.040546	BG very fast	BG very fast	1
SW fine roots	CH_4	0.000451	AG fast	AG fast	1
SW fine roots	CO	0.004055	BG fast	BG fast	1
HW merchantable	HW stem snag	1	Medium	Medium	1
HW foliage	CO_2	0.9	AG slow	AG slow	1
HW foliage	CH_4	0.01	BG slow	BG slow	1
HW foliage	CO	0.09	SW stem snag	Medium	1
HW other	HW branch snag	0.99905	SW branch snag	AG fast	1
HW other	CO_2	0.000855	HW stem snag	Medium	1
HW other	CH_4	0.00001	HW branch snag	AG fast	1
HW other	CO	0.000086			
HW submerchantable	HW branch snag	0.989825			
HW submerchantable	CO_2	0.0091575			
HW submerchantable	CH_4	0.00010175			
HW submerchantable	CO	0.00091575			
HW coarse roots	AG fast	0.5			
HW coarse roots	BG fast	0.5			
HW fine roots	AG very fast	0.456205			
HW fine roots	BG very fast	0.5			
HW fine roots	CO_2	0.039415			
HW fine roots	CH_4	0.000438			
HW fine roots	CO	0.003942			
AG very fast	AG very fast	0.031467			
AG very fast	CO_2	0.87168			
AG very fast	CH_4	0.009685			
AG very fast	CO	0.087168			
BG very fast	BG very fast	1			
AG fast	AG fast	0.358407			
AG fast	CO_2	0.577434			
AG fast	CH_4	0.006416			
AG fast	CO	0.057743			
BG fast	BG fast	1			
Medium	Medium	0.60786			
Medium	CO_2	0.352926			
Medium	CH_4	0.003921			
Medium	CO	0.035293			
AG sow	AG slow	0.909897			
AG slow	CO_2	0.081093			
AG slow	CH_4	0.000901			
AG slow	CO	0.008109			
BG slow	BG slow	1			
SW stem snag	Medium	1			
SW branch snag	AG fast	1			
HW stem snag	Medium	1			
HW branch snag	AG fast	1			

Note: SW, softwood; HW, hardwood; AG, aboveground, BG, belowground.

Table 6. Mean (SE) (n = 3) C pool stocks (t·ha^{-1}) for balsam fir (*Abies balsamea*) sites estimated by field measurement and by the CBM-CFS3 using default settings and the altered parameters (highlighted in bold).

		Originating disturbance					
		Insect		Harvest			
Ecosytem pool	Estimation	Stand age 1–2 years	Stand age 33 years	Stand age 1–2 years	Stand age 32–41 years	Harvest (thinned), stand age 32–41 years	Unknown, stand age 86–109 years
HW$_{\mathrm{Abio}}$	Measured	2.2 (0.8)	6.4 (0.4)	1.8 (0.6)	5.2 (2.5)	0.9 (0.8)	6.1 (1.7)
	Modeled (default)	3.3 (0.1)	0.2 (0.3)	4.4 (0.2)	0.9 (0.2)	0.0 (0.0)	8.5 (0.2)
HW$_{\mathrm{roots}}$	Measured	0.5 (0.2)	1.4 (0.1)	0.4 (0.1)	1.2 (0.6)	0.2 (0.2)	1.4 (0.4)
	Modeled (default)	2.5 (0.0)	0.4 (0.1)	3.0 (0.1)	1.1 (0.2)	0.0 (0.0)	4.5 (0.1)
SW$_{\mathrm{Abio}}$	Measured	7.0 (2.9)	26.5 (3.9)	0.3 (0.3)	53.2 (10.6)	45.2 (1.8)	63.7 (3.4)
	Modeled (default)	7.5 (0.8)	33.2 (1.0)	0.1 (0.1)	49.2 (6.3)	48.6 (8.6)	74.6 (1.3)
SW$_{\mathrm{roots}}$	Measured	1.5 (0.6)	5.9 (0.9)	0.1 (0.1)	11.8 (2.4)	10.0 (0.4)	14.1 (0.8)
	Modeled (default)	1.7 (0.2)	7.4 (0.2)	0.0 (0.0)	10.9 (1.4)	10.8 (1.9)	16.6 (0.3)
Live tree total	Measured	10.9 (4.3)	39.2 (4.6)	2.3 (0.3)	70.6 (13.7)	56.2 (2.7)	84.2 (5.4)
	Modeled (default)	15.0 (0.9)	41.2 (1.3)	7.5 (0.2)	62.1 (7.4)	59.4 (10.5)	104.1 (1.4)
Snag stems	Measured	17.8 (1.8)	1.4 (0.2)	0.4 (0.1)	1.1 (0.5)	0.0 (0.0)	10.0 (2.1)
	Modeled (default)	24.6 (0.8)	8.1 (1.3)	0.0 (0.0)	0.4 (0.1)	0.4 (0.2)	6.8 (0.1)
	Modeled (altered)	**17.6 (0.7)**	**0.8 (0.1)**	**0.0 (0.0)**	**0.3 (0.1)**	**0.3 (0.1)**	**2.7 (0.1)**
Snag branches	Measured	12.4 (1.5)	0.2 (0.0)	0.0 (0.0)	0.8 (0.2)	0.0 (0.0)	1.3 (0.2)
	Modeled (default)	15.7 (0.3)	0.9 (0.0)	0.0 (0.0)	1.2 (0.1)	1.1 (0.2)	2.2 (0.0)
	Modeled (altered)	**12.4 (0.2)**	**0.5 (0.0)**	**0.0 (0.0)**	**0.8 (0.1)**	**0.7 (0.1)**	**1.3 (0.0)**
CWD	Measured	5.2 (0.4)	8.2 (0.4)	14.2 (7.8)	3.6 (0.4)	7.3 (3.1)	9.5 (0.9)
	Modeled (default)	15.6 (0.4)	15.1 (1.9)	21.7 (1.7)	7.6 (0.2)	7.6 (0.2)	13.2 (0.7)
	Modeled (altered)	**12.2 (0.0)**	**11.5 (1.8)**	**11.8 (0.5)**	**2.9 (0.2)**	**2.9 (0.2)**	**7.2 (0.0)**
S&FWD	Measured	2.4 (0.3)	3.9 (0.4)	10.0 (0.5)	2.9 (0.2)	3.2 (0.5)	2.9 (0.2)
	Modeled (default)	4.3 (0.0)	5.0 (0.0)	35.5 (0.9)	5.7 (0.3)	5.4 (0.7)	12.6 (0.1)
	Modeled (altered)	**1.5 (0.1)**	**1.5 (0.2)**	**24.4 (1.4)**	**2.6 (0.3)**	**2.4 (0.5)**	**4.7 (0.1)**
Organic soil horizons	Measured	123.3 (31.1)	43.0 (8.7)	31.0 (5.3)	38.5 (12.5)	35.0 (6.7)	48.0 (1.0)
	Modeled (default)	55.6 (0.3)	43.7 (0.9)	62.3 (0.6)	45.1 (0.3)	44.4 (1.0)	60.4 (0.3)
	Modeled (altered)	**55.4 (0.2)**	**43.9 (0.9)**	**61.9 (0.5)**	**44.5 (0.3)**	**43.7 (1.0)**	**59.7 (0.3)**
Mineral soil horizons	Measured	178.8 (42.4)	49.1 (11.3)	65.5 (12.0)	52.9 (5.2)	88.0 (11.4)	97.2 (11.6)
	Modeled (default)	110.1 (0.1)	109.2 (1.5)	115.7 (1.0)	111.3 (0.6)	111.1 (0.8)	127.6 (0.2)
	Modeled (altered)	**110.1 (0.1)**	**109.2 (1.5)**	**115.7 (1.1)**	**111.1 (0.6)**	**110.9 (0.8)**	**127.5 (0.2)**
Dead coarse roots	Measured	na	na	na	na	na	na
	Modeled (default)	19.4 (0.6)	1.2 (0.0)	15.2 (0.2)	1.6 (0.0)	1.4 (0.2)	4.4 (0.0)
	Modeled (altered)	**19.4 (0.6)**	**1.2 (0.0)**	**15.2 (0.2)**	**1.6 (0.0)**	**1.4 (0.2)**	**4.4 (0.0)**
Ecosystem total (no DCR)	Measured	350.8 (59.9)	145.0 (22.7)	123.4 (7.1)	170.4 (11.3)	189.7 (13.2)	253.1 (7.4)
	Modeled (default)	240.9 (0.6)	223.2 (4.5)	242.7 (1.3)	233.4 (8.6)	229.4 (13.2)	326.9 (1.9)
	Modeled (altered)	**224.2 (0.6)**	**208.6 (3.4)**	**221.3 (0.3)**	**224.3 (8.6)**	**220.3 (13.0)**	**307.2 (1.3)**

Note: The altered parameter set is shown in Table 4. HW, hardwood; SW, softwood; Abio, aboveground biomass; CWD, coarse woody debris; S&FWD, small and fine woody debris; DCR, dead coarse roots; na, not applicable.

Table 7. Mean (SE) (n = 3) C pool stocks (t·ha^{-1}) for black spruce (*Picea mariana*) sites estimated by field measurement and by the CBM-CFS3 using default settings and the altered parameters (highlighted in bold).

		Originating disturbance					
		Burned			Harvested		
Ecosytem pool	Estimation	Stand age 0–2 years	Stand age 34 years	Stand age 68–92 years	Stand age 2–3 years	Stand age 34–39 years	Stand age 63–72 years
$\mathrm{HW}_{\mathrm{Abio}}$	Measured	0.0 (0.0)	0.2 (0.1)	2.2 (1.7)	0.0 (0.0)	0.1 (0.0)	5.8 (4.0)
	Modeled (default)	0.0 (0.0)	0.6 (0.5)	1.0 (0.1)	0.0 (0.0)	0.5 (0.3)	1.6 (0.1)
$\mathrm{HW}_{\mathrm{roots}}$	Measured	0.0 (0.0)	0.0 (0.0)	0.5 (0.4)	0.0 (0.0)	0.0 (0.0)	1.3 (0.9)
	Modeled (default)	0.0 (0.0)	0.7 (0.5)	1.2 (0.1)	0.0 (0.0)	0.6 (0.3)	1.6 (0.0)
$\mathrm{SW}_{\mathrm{Abio}}$	Measured	1.6 (1.6)	23.2 (2.5)	74.1 (10.7)	0.1 (0.1)	32.6 (5.0)	69.2 (2.7)
	Modeled (default)	0.0 (0.0)	27.2 (2.5)	72.7 (1.9)	0.1 (0.1)	37.6 (3.2)	54.4 (3.7)
$\mathrm{SW}_{\mathrm{roots}}$	Measured	0.3 (0.3)	5.2 (0.6)	16.4 (2.4)	0.0 (0.0)	7.2 (1.1)	15.4 (0.6)
	Modeled (default)	0.0 (0.0)	6.0 (0.6)	16.1 (0.4)	0.0 (0.0)	8.4 (0.7)	12.1 (0.8)
Live tree total	Measured	1.9 (1.9)	28.6 (3.1)	92.9 (14.7)	0.1 (0.1)	39.9 (6.1)	90.7 (7.4)
	Modeled (default)	0.0 (0.0)	34.5 (2.1)	91.1 (2.2)	0.2 (0.1)	47.1 (4.1)	69.8 (4.3)
Snag stems	Measured	19.3 (6.0)	0.1 (0.1)	2.2 (1.8)	0.0 (0.0)	0.0 (0.0)	0.5 (0.2)
	Modeled (default)	24.6 (0.3)	7.4 (0.0)	4.3 (0.4)	0.0 (0.0)	0.2 (0.1)	2.9 (0.4)
	Modeled (altered)	**21.8 (0.8)**	**0.7 (0.0)**	**1.6 (0.1)**	**0.0 (0.0)**	**0.2 (0.0)**	**1.0 (0.1)**
Snag branches	Measured	10.6 (1.2)	0.2 (0.1)	1.5 (0.5)	1.6 (0.2)	0.6 (0.1)	1.0 (0.5)
	Modeled (default)	15.1 (1.2)	0.7 (0.1)	1.9 (0.1)	0.0 (0.0)	0.9 (0.1)	1.6 (0.1)
	Modeled (altered)	**12.7 (1.9)**	**0.5 (0.1)**	**1.2 (0.0)**	**0.0 (0.0)**	**0.6 (0.1)**	**0.9 (0.0)**
CWD	Measured	3.6 (2.1)	5.5 (3.3)	3.6 (3.5)	4.8 (1.1)	3.3 (1.3)	1.6 (0.8)
	Modeled (default)	10.7 (0.3)	16.6 (0.0)	9.8 (1.1)	18.4 (4.0)	5.2 (1.1)	7.4 (1.3)
	Modeled (altered)	**7.9 (1.4)**	**12.4 (0.0)**	**4.9 (0.5)**	**10.4 (2.3)**	**1.9 (0.3)**	**3.7 (0.7)**
S&FWD	Measured	1.7 (0.5)	8.0 (0.8)	2.6 (1.0)	13.0 (1.0)	2.4 (0.7)	3.3 (0.9)
	Modeled (default)	6.0 (0.7)	2.9 (0.2)	11.2 (0.1)	28.1 (3.4)	4.8 (0.4)	8.1 (0.3)
	Modeled (altered)	**4.2 (0.6)**	**0.3 (0.1)**	**5.1 (0.1)**	**13.9 (2.0)**	**2.1 (0.2)**	**3.4 (0.1)**
Organic soil horizons	Measured	50.4 (9.8)	60.5 (10.0)	45.5 (3.0)	42.6 (4.2)	34.1 (2.0)	43.5 (4.5)
	Modeled (default)	29.2 (0.5)	33.6 (0.4)	43.3 (0.1)	47.5 (4.7)	36.7 (1.9)	36.3 (1.4)
	Modeled (altered)	**31.0 (0.3)**	**35.1 (0.4)**	**45.0 (0.2)**	**49.2 (4.8)**	**37.0 (2.0)**	**37.9 (1.6)**
Mineral soil horizons	Measured	74.0 (18.2)	100.3 (23.8)	104.5 (19.3)	104.2 (40.5)	136.5 (31.3)	97.0 (8.6)
	Modeled (default)	85.9 (0.1)	91.2 (0.1)	90.9 (1.7)	91.0 (8.6)	81.8 (5.0)	78.2 (3.8)
	Modeled (altered)	**99.9 (0.4)**	**104.9 (0.1)**	**105.5 (2.4)**	**105.5 (10.1)**	**92.2 (6.4)**	**90.7 (4.6)**
Total dead coarse roots	Measured	na	na	na	na	na	na
	Modeled (default)	13.8 (0.6)	3.2 (0.0)	1.2 (0.0)	13.4 (2.2)	1.2 (0.2)	2.4 (0.2)
	Modeled (altered)	**13.8 (0.6)**	**3.2 (0.0)**	**1.2 (0.0)**	**13.4 (2.2)**	**1.2 (0.2)**	**2.4 (0.2)**
Ecosystem total (no DCR)	Measured	161.5 (26.9)	203.2 (32.8)	252.8 (29.6)	166.3 (39.8)	216.8 (33.0)	237.6 (10.9)
	Modeled (default)	171.5 (0.2)	186.9 (2.9)	252.5 (5.4)	185.2 (21.5)	176.7 (12.6)	204.3 (11.5)
	Modeled (altered)	**177.5 (0.5)**	**188.4 (2.8)**	**254.4 (4.9)**	**179.2 (19.0)**	**181.1 (11.8)**	**207.4 (10.7)**

Note: The altered parameter set is shown in Table 4. HW, hardwood; SW, softwood; Abio, aboveground biomass; CWD, coarse woody debris; S&FWD, small and fine woody debris; DCR, dead coarse roots; na, not applicable.

ters were altered, GOF statistics were run again on all pools to determine if model accuracy was improved. Results are reported only for the alternative parameter set that provided the best fit from the values that were tested. Four parameter changes were implemented in the alternative parameter set: the medium basal decay rate from 0.0374 to 0.06, the aboveground fast basal decay rate from 0.1435 to 0.28, the snag stem to medium pool transfer rate from 0.032 to 0.10, and snag branch to aboveground fast transfer rate from 0.10 to 0.20 (Table 4).

Results

Comparison of the CBM-CFS3 and field estimated ecosystem C pools

Measured estimates for the CBM-CFS3 pools were calculated for balsam fir (Table 6) and black spruce (Table 7) and reported along with modeled estimates from simulations using the model's default parameters and for the alternative set of parameters (Table 4) that best reduced error and (or) bias in some pool estimates. In all, 14 pools (Tabless 8, 9, and 10) were analyzed for GOF. Some pools represent the sum of other pools (e.g., live tree total is the sum of all above- and belowground live tree pools).

When all strata were grouped together for the GOF analysis (Table 8), LOFIT F was less than critical $F_{(p=0.05)}$ and $E < E_{(95\%)}$ (no significant bias) for all pools except for $\mathrm{HW_{roots.}}$ Two pools, in addition to $\mathrm{HW_{roots}}$, exceeded a standard for bias of no greater than 50% error. These were small and fine woody debris (S&FWD) and CWD that were overestimated by 130% and 111%, respectively (Table 8).

At this scale, the correlation (r) between modeled and measured $\mathrm{SW_{Abio}}$ and $\mathrm{SW_{roots}}$ was high and significant as was the correlation for live tree total that includes $\mathrm{HW_{Abio}}$ and $\mathrm{HW_{roots}}$ (Table 8). The correlation for $\mathrm{HW_{roots}}$ was not significant. Because HW biomass is generally low in these ecosystems (Tables 6 and 7), its contribution to total tree biomass is small and, therefore, had little impact on the correlation between modeled and measured estimates for total tree biomass. Correlations were high and significant for snag stem and snag branch pools and were lower but still significant for CWD and S&FWD pools. The correlation for total ecosystem (excluding organic and mineral soil) was high and significant (Table 8).

When all sites were considered, correlations for the organic and mineral soil pools were not significant. Although we reported these values for completeness and transparency, Smith and Smith (2007) stated that r should be calculated only if there is an observed trend in the measured data, which there was not for the two soil pools. Despite the low correlation for the soil organic horizons, the total ecosystem C still had a significant correlation (0.67) even when the organic horizon pool was included in the total. If the young fir stands (F/H/Y and F/I/Y) with the highest residuals are removed from the sites, the correlation increased to 0.90 and was significant. Once the mineral soil pool was included in the ecosystem total, the correlation was low (0.33) and not significant.

The altered parameter set reduced bias for all snag and woody debris pools below the 50% standard and did not negatively impact other GOF statistics for snag stems, branches, and S&FWD (Table 8). The correlation for CWD was, however, negatively impacted, as it was reduced to 0.48 and was not significant. Despite this, all GOF statistics for total ecosystem C (excluding soil) improved as a result of the altered parameter set.

Results at this scale suggest that overall model accuracy is high for the default parameters and was further improved, for the most part, with the alternative parameter set. The major exception was the poor correlation for mineral and organic soil pools. However, these pools exhibited no significant trend in the measured data.

Model accuracy was tested again after grouping by dominant species, fir or spruce, to test if the model performs equally well for the two dominant species. The GOF statistics for SW and HW biomass pools and the total live tree pool were similar to those reported for the whole data set. Results for default model runs for DOM, soil, and total ecosystem pools are shown in Table 9 along with estimates resulting from runs where parameters were altered.

In all cases for spruce and fir, the LOFIT was not significant and $E > E_{(95\%)}$ in only one instance: S&FWD for fir. For fir, one additional pool, CWD, exceeded the 50% standard for bias, and for spruce, three pools snag stems, S&FWD, and CWD — exceeded the 50% standard. After grouping by species, the correlation for the snag stems and snag branches pools remained high (Table 9) and similar to those for all strata combined (Table 8). However, the bias for spruce snag stems exceeded the 50% standard where model predictions were greater than measured estimates. Increasing the snag stem fall rate from 0.032 to 0.100 (and snag branches from 0.10 to 0.20) reduced the bias for both snag pools for spruce and fir without negatively impacting the LOFIT or correlation statistics. The bias in default modeled predictions of the S&FWD was high for fir (>50% and >95% CI) and >50% for spruce where modeled estimates were greater than measured. Increasing the base decay rate of the S&FWD pool from 0.1435 to 0.28 lowered the bias below 50% for both species without negatively impacting the LOFIT or correlation for fir. LOFIT was not negatively impacted for spruce, but the correlation remained nonsignificant regardless of whether the default or altered base decay rate was applied to the S&FWD pool.

After grouping by species, the default model bias (overestimation) for the CWD pool was slightly >50% for fir (–68%) and much greater for spruce (–202%). The maximum increase to the CWD base decay rate reduced bias to –1% for fir but did not significantly increase the correlation. The bias for spruce was reduced to –83% for CWD and resulted in a significant correlation of 0.82 (Table 9).

Even after grouping by species, all of the GOF statistics were good (Table 9) and similar to the results for all strata (Table 8) for total ecosystem C (excluding soil pools). Once the organic soil horizon pool was included in the total, the correlation for spruce remained high (0.87) and significant but low (0.52) and not significant for fir. The correlation for the mineral soil pool was low and not significant and negatively impacted the correlation for the ecosystem total once included in that pool.

Model accuracy was tested again after grouping by natural (burned or insect killed) or anthropogenic (harvest) stand-originating disturbance type to determine if the model

Table 8. CBM pool goodness-of-fit statistics from default runs.

	Error (LOFIT)		Bias (E)		Correlation (r)	
CBM pool	LOFIT	F^a	E	95% CI	r	F^b
$\mathrm{HW}_{\mathrm{Abio}}$	274	0.07	32	518	0.42	2.18
$\mathrm{HW}_{\mathrm{roots}}$	105*	8.11	–675*	408	0.48	3.06
$\mathrm{SW}_{\mathrm{Abio}}$	1 369	0.00	–2	146	0.97*	128.12
$\mathrm{SW}_{\mathrm{roots}}$	68	0.00	–2	146	0.97*	176.25
Live tree total	3 165	0.00	–3	158	0.96*	123.77
Snag stems	576	0.04	–50	316	0.93*	63.59
Snag branches	106	0.02	–44	198	0.99*	874.98
S&FWD	3 399	0.45	–130	153	0.77*	14.33
CWD	2 020	0.15	–111	451	0.67*	7.98
Ecosystem total (no soil)	16 368	0.02	–28	154	0.90*	41.79
Organic soil horizons	21 345	0.03	10	211	0.17	0.31
Ecosystem total (no mineral soil)	32 224	0.01	–11	118	0.67*	8.28
Mineral soil	58 896	0.02	–5	261	–0.20	0.43
Ecosystem total (with organic and mineral soil)	140 423	0.01	–8	154	0.33	1.22

Note: An asterisk indicates statistically significant at $p \leq 0.05$ for LOFIT and r or error falls outside of the 95% confidence interval for E. HW, hardwood; SW, softwood; Abio, aboveground biomass; S&FWD, small and fine woody debris; CWD, coarse woody debris.

[a] Critical $F = 2.12$, degrees of freedom = 12 – 2,36 – 2 = 10,34.

[b] Critical $F = 4.96$, degrees of freedom = 12 – 2 = 10.

performed equally well for different disturbance types (Table 10). Results for tree biomass pools were similar to those for all strata and for strata grouped by dominant species. For each of the remaining pools in each disturbance type group, the LOFIT was not significant, indicating that model error was not greater than measurement error (Table 10). In one case, the S&FWD pool in the harvested group, $E > E_{(95\%)}$, indicating a significant bias. For the harvested group, snag branches, and CWD pools, bias exceeded the 50% standard, and for the natural disturbances group, bias exceeded the 50% standard for S&FWD and CWD. In all cases where the bias was significant, modeled estimates were greater than measured estimates (Table 10).

The altered parameter set, which generally reduced bias while not negatively impacting LOFIT and correlation statistics when sites were grouped by species (Table 9), did not generally produce the same degree of improvements when sites were grouped by disturbance type (Table 10). Increasing snag and snag branch fall rates reduced bias for snag branches but increased bias above the 50% standard for snag stems in the harvested group where modeled estimates were generally lower than measured. Increasing the base decay rate of the S&FWD pool had a positive outcome for harvest-origin strata by reducing bias and not negatively impacting LOFIT or correlation statistics. For strata originating from natural disturbances, bias in the S&FWD pool was reduced, but the correlation remained poor for both default (–0.47) and altered (–0.70) base decay rates. Similarly for CWD, increasing the base decay rate reduced bias, but not below the 50% standard, and did not improve the correlation for naturally disturbed strata. For the CWD pool in harvest-origin strata, the bias was significantly reduced and the correlation minimally impacted (0.73–0.69) by increasing the base decay rate, although the correlation in both cases was not significant.

Results for the total ecosystem, organic, and mineral soil C pools when grouped by disturbance type (Table 10) were similar to those for all strata (Table 8) and for strata grouped by species (Table 9). That is, model accuracy was high for total ecosystem C excluding soil. Error and bias were low for organic and mineral soil horizon soil pools but with low and nonsignificant correlations. Once the organic soil horizon pool was added to the total ecosystem C, the GOF statistics remained good for the harvested strata but the correlation for naturally disturbed strata became nonsignificant. If the young fir strata with the largest residuals were removed, the correlations for total ecosystem C for both groups were high (0.96 and 0.90) and significant. Including mineral soil C in the total ecosystem C estimate had a large negative impact on correlations (Table 10).

Discussion

The GOF statistics comparing modeled and measured estimates including all sites show that model accuracy is high for a suite of sites representative of the species (F and S), disturbance origins (B, I, and H), and stand ages (Y, M, and O) in the boreal forest landscape of Newfoundland (Tables 8, 9, and 10). At this scale, all GOF statistics were very good for nine of the 14 pools tested. For these nine pools, the LOFIT was not significant and correlations were significant, ranging in value from 0.67 to 0.99. The altered parameter set that increased the snag and snag branch fall rates and increased the woody debris (CWD and S&FWD) pool base decay rates improved overall model accuracy, except that increasing the base decay rate for CWD reduced for this pool the correlation, which was not significant. This suggests that process(es) affecting CWD dynamics, other than decay, must be represented better in the model to improve the accuracy of estimates for this pool in small-diameter boreal forest ecosystems. However, the remaining issue with CWD did not negatively impact the GOF for total ecosystem C (excluding soil) for which the GOF statistics were fine.

Three of the remaining compared pools were the organic and mineral soil horizons and total ecosystem C including

Table 9. Goodness-of-fit statistics (default and altered parameter sets) for dead organic matter, soil, and total ecosystem pools grouped by lead species, balsam fir (*Abies balsamea*) and black spruce (*Picea mariana* (n = 6 for each species).

		Balsam fir						Black spruce					
		Error (LOFIT)		Bias (E)		Correlation (r)		Error (LOFIT)		Bias (E)		Correlation (r)	
Parameter set	CBM pool	LOFIT	F^a	E	95% CI	r	F^b	LOFIT	F^a	E	95% CI	r	F^b
Default	Snag stems	307	0.08	–32	199	0.91*	19.11	269	0.06	–74	475	0.96*	44.28
	Snag branches	40	0.03	–42	171	1.00*	971.53	66	0.06	–47	227	0.99*	381.83
	S&FWD	2279	1.68	170*	108	0.95*	37.54	1 119	0.47	–97	190	0.74	4.74
	CWD	725	0.13	–68	345	0.76	5.32	1 295	0.93	–202	677	0.81	7.69
	Ecosystem total (no soil)	10 324	0.04	–31	136	0.85*	10.67	6 044	0.02	–25	174	0.95*	40.60
	Organic soil horizons	17 554	0.08	2	260	0.20	0.17	3 792	0.03	18	154	–0.40	0.78
	Ecosystem total (no mineral soil)	26 888	0.03	–16	126	0.52	1.45	5 337	0.01	–6	108	0.87*	11.97
	Mineral soil	47 120	0.08	–29	224	0.01	0.00	11 776	0.02	16	292	–0.16	0.11
	Ecosystem total (with organic and mineral soil)	130 040	0.05	–21	130	0.34	0.51	10 384	0.00	5	180	0.77	5.89
Altered	Snag stems	162	0.04	29	199	0.92*	21.88	23	0.01	–12	475	1.00*	700.15
	Snag branches	10	0.01	6	171	1.00*	1138.60	17	0.02	–15	227	0.99*	249.36
	S&FWD	651	0.48	–46	108	0.97*	72.77	215	0.09	6	190	0.67	3.19
	CWD	274	0.05	–1	345	0.46	1.06	314	0.22	–83	677	0.82*	8.47
	Ecosystem total (no soil)	1 825	0.01	–7	136	0.94*	28.92	1 651	0.01	–3	174	0.97*	62.01
	Organic soil horizons	17 450	0.08	3	260	0.22	0.20	3 325	0.03	15	154	–0.35	0.56
	Ecosystem total (no mineral soil)	19 411	0.02	–3	126	0.54	1.65	3 908	0.01	5	108	0.91*	18.18
	Mineral soil	47 004	0.08	–29	224	0.01	0.00	8 088	0.01	3	292	–0.36	0.38
	Ecosystem total (with organic and mineral soil)	110 378	0.04	–14	130	0.33	0.47	8 503	0.00	4	180	0.81	7.64

Note: An asterisk indicates statistically significant at $p \leq 0.05$ for LOFIT and r or error falls outside of the 95% confidence interval for E. The altered parameter set is shown in Table 4. S&FWD, small and fine woody debris; CWD, coarse woody debris.

[a] Critical F = 3.01, degrees of freedom = 6 – 2,18 – 2 = 4,16.

[b] Critical F = 7.71, degrees of freedom = 6 – 2 = 4.

Table 10. Goodness-of-fit statistics (default and altered parameter sets) for dead organic matter, soil, and total ecosystem pools grouped by disturbance group (n = 6 for natural disturbances, n = 7 for harvested).

		Natural disturbances						Harvested					
		Error (LOFIT)		Bias (*E*)		Correlation (*r*)		Error (LOFIT)		Bias (*E*)		Correlation (*r*)	
Parameter set	CBM pool	LOFIT	F^a	*E*	95% CI	*r*	F^b	LOFIT	F^a	*E*	95% CI	*r*	F^b
Default	Snag stems	557	0.07	–48	308	0.90*	178.86	48	0.04	11	314	0.92*	29.60
	Snag branches	99	0.04	–37	175	0.99*	364.14	9	0.20	–106	380	0.85*	13.11
	S&FWD	647	0.68	–95	178	–0.47	1.16	3 033	0.90	–165*	134	0.91*	23.67
	CWD	1 143	0.43	–127	376	0.44	0.95	919	0.16	–83	440	0.73	5.65
	Ecosystem total (no soil)	8 834	0.03	–33	152	0.98*	122.49	10 405	0.03	–24	136	0.86*	14.49
	Organic soil horizons	17 755	0.07	28	218	0.37	0.63	4 055	0.03	–22	169	0.04	0.02
	Ecosystem total (no mineral soil)	12 315	0.01	–3	146	0.76	5.32	25 555	0.03	–24	71	0.72	5.54
	Mineral soil	28 974	0.04	–2	266	0.16	0.11	32 694	0.04	–12	239	–0.58	2.58
	Ecosystem total (with organic and mineral soil)	71 859	0.02	–2	169	0.48	1.17	84 894	0.03	–18	115	0.28	0.41
Altered	Snag stems	182	0.02	12	308	0.94*	29.92	161	0.14	63	314	0.95*	42.79
	Snag branches	25	0.01	–1	175	0.97*	72.23	2	0.05	–27	380	0.82*	10.27
	S&FWD	242	0.25	20	178	–0.70	3.75	634	0.19	–42	134	0.84*	11.65
	CWD	398	0.15	–57	376	0.20	0.16	205	0.04	8	440	0.69	4.47
	Ecosystem total (no soil)	1 049	0.00	–8	152	0.99*	201.86	2 861	0.01	–3	136	0.93*	33.71
	Organic soil horizons	17 318	0.06	27	218	0.37	0.62	3 871	0.03	–22	169	0.07	0.01
	Ecosystem total (no mineral soil)	13 769	0.01	8	146	0.73	4.55	11 248	0.01	–10	71	0.81*	9.85
	Ecosystem total (no mineral soil)[c]	3 138	0.01	0	122	0.96*	40.25	4 431	0.01	–4	61	0.90*	16.21
	Mineral soil	29 811	0.04	–9	266	0.12	0.06	28 034	0.04	–18	239	–0.50	1.66
	Ecosystem total (with soil)	71 565	0.02	0	169	0.47	0.97	56 090	0.02	–14	115	0.41	1.00

Note: An asterisk indicates statistically significant at $p \leq 0.05$ for LOFIT and r or error falls outside of the 95% confidence interval for E. The altered parameter set is shown in Table 4.S&FWD, small and fine woody debris; CWD, coarse woody debris.

[a] Critical F = 3.01 for natural disturbances, degrees of freedom = 6 – 2, 18 – 2 = 4,16 and for harvested = 2.45, degrees of freedom = 7 – 2,21 – 2 = 5,19.

[b] Critical F = 7.71 for natural disturbances, degrees of freedom = 6 – 2 = 4 and for harvested = 6.61, degrees of freedom = 7 – 2 = 5.

[c] BFYH outlier removed from harvested group, BFYI outlier removed from natural disturbances group.

the soil pools. The LOFIT and bias were not significant for these pools but correlations were poor. However, the measured data showed no observable trend that the model could be expected to reflect. Because the soil C pools were large and lacked an observable trend, they had a large negative impact on the correlation of ecosystem C stocks after soil C was included in the ecosystem total.

Lastly, the CBM-CFS3 was challenged to represent the dynamics of the hardwood biomass component, particularly in fir stands. The model tended to underestimate HW_{Abio} in middle-aged fir stands (F/H/M and F/I/M) (Table 6) and this was reflected in poor correlations for the HW_{Abio} and HW_{roots}. Underestimation of HW_{Abio} in these cases may indicate that yield curves for the hardwood component of the balsam fir mixed stands inaccurately reflected their productivity. The large bias in HW_{root} may have resulted from the CBM-CFS3 applying the equations of Li et al. (2003) to estimate hardwood roots. The CBM-CFS3 applies the Li et al. (2003) equations to the hardwood component of softwood forests in a two-step process. First, the CBM-CFS3 estimates what the hardwood and softwood root biomass would be if all aboveground live tree C were of either softwood or hardwood origin. The amount of softwood and hardwood root biomass in these totals are then calculated based on the proportions represented in aboveground biomass. Where little live tree C is left, such as after disturbances, and it is composed of few large diameter at breast height hardwoods that individually have low belowground:aboveground biomass ratios, the Li et al. (2003) equations will overestimate hardwood root biomass. The Li et al. (2003) equations estimate belowground biomass based on aboveground biomass per hectare, where smaller aboveground biomass per hectare equates to larger predicted belowground to aboveground biomass ratios. Thus, when few residual large diameter at breast height hardwood trees survive disturbances, the implementation of the Li et al. (2003) equations in the model appears to overestimate root biomass for the few surviving trees; however, the C pool amounts are small compared with ecosystem totals (Tables 6 and 7).

Regardless of whether the whole data set (Table 8) or groups of strata (by species or disturbance type) (Tables 9 and 10) were tested, model accuracy for the dominant softwood biomass pools was good (low error and bias and high correlation). However, because a yield curve is the input to the CBM-CFS3 used to represent growth, any steps that can be taken, based on prior knowledge, to improve yield curve selection to better represent site simulations for validation of biomass pools will provide the most meaningful test of the model's ability to predict not only biomass but also DOM and soil C pools. Failure to select the appropriate yield curve will result in incorrect estimates of site productivity, which in turn will affect all estimates of DOM pools. Even though GOF statistics were good for softwood and total biomass where both field-measured and modeled live tree C stocks increased with forest age, differences between measured and modeled live tree C can be observed. Growth curves assigned to sites from characteristics observed from aerial photographs likely differ to some extent from actual site growth and yield. If the measured forest had accumulated merchantable volume as yield curves predicted, very minor differences in field-measured and modeled live tree C are expected because modeled live tree C is based on merchantable yield estimated from growth curves. For example, assigned yield curves do not account for potential growth reductions from snag shading in unsalvaged naturally disturbed stands, which potentially account for some difference between measured and modeled live tree C in middle-aged naturally disturbed strata (F/I/M and S/B/M). In addition, senescence of old-growth fir (F/U/O) was well underway in the field as indicated by large measured snag C and a cohort of <9 cm diameter at breast height live trees (Moroni et al. 2010) (Table 3), yet yield curves for these plots did not indicate significant senescence at the ages examined. Thus, closer values of measured and modeled live tree C would have been likely for F/U/O if F/U/O if stand dynamics had not deviated from assigned growth and yield curves.

Growth in merchantable volume of thinned strata was projected to be similar to growth of unthinned strata because there are few data available to establish growth curves for thinned stands. Thinning in Newfoundland commenced in the mid- to late 1970s, becoming widespread only in the 1980s. Thus, there is concern that thinned stands may not accumulate biomass as fast as growth curves project (B. English, Newfoundland and Labrador Department of Natural Resources, personal communication (2005)). Differences in middle-aged thinned harvested fir (F/HT/M) measured and modeled live tree C potentially result from overly ambitious yield curves for thinned stands provided to the CBM-CFS3. A well-prescribed thinning will virtually eliminate mortality due to self-thinning, as was observed by Moroni et al. (2010) with few snags encountered in the middle-aged thinned fir strata, whereas the middle-aged unthinned fir strata contained more snags. The CBM-CFS3 currently lacks the facility to reduce stem mortality rates following thinning. This could contribute to overestimation of mortality rates following thinning if stem mortality rates in thinned stands are indeed reduced as observed in middle-aged thinned fir (F/HT/M) (Table 6). Although the modeled snag C mass from self thinning in balsam fir was low for unthinned middle-aged fir (Table 6), more snags were produced in unthinned fir than in thinned fir and it would be more accurate for the CBM-CFS3 to represent post-thinning dynamics in fir stands of this type by reducing stem turnover rates for some years after thinning.

Where there are deviations between actual forest growth and that represented by the yield curves provided to the CBM-CFS3, these differences are expected to impact comparisons of other measured and modeled C pools, in particular those of dead wood. Therefore, careful consideration should be given to yield curve selection when comparing CBM-CFS3 output with field-measured results for specific sites to ensure, as far as is practicable, that the yield curve reflects stand development of the specific sites under consideration.

The impact of disturbance history and time since disturbance on snag C is captured by the CBM-CFS3. Measured and modeled stem snag C were much larger in recently naturally disturbed strata (F/I/Y and S/B/Y) than in recently harvested strata (F/H/Y and S/H/Y) (Tables 6 and 7). The observed collapse of snags between recently naturally disturbed (F/I/Y and S/B/Y) and middle-aged naturally disturbed strata (F/I/M and S/B/M) is also captured by the model. However, in general, field-measured snag C was lower than modeled snag C (Tables 6 and 7) and the GOF statistics for the grouped data indicate that the CBM-CFS3 overestimated spruce snag stems (Table 9) and snag branches for the harvested disturbance type (Table 10). These results, plus the difference in snag C between measured and modeled middle-aged naturally disturbed strata, in particular, indicate that the default CBM-CFS3 snag fall rate was too low for the examined forests. The CBM-CFS3 simulates snag fall using an exponential decay curve where each year, a percentage of standing snag C mass is transferred to downed CWD, the medium DOM pool in the model. The CBM-CFS3 default settings assume an annual transfer rate of 3.2% for snag stem and 10% for snag branch C mass (Table 4). To describe the observed reduction in snag C from amounts encountered in recently naturally disturbed strata to those in middle-aged naturally disturbed strata, annual snag stem fall rates and snag branch fall rates of ~10%·year^{-1} and 20%·year^{-1}, respectively, are required. These values are consistent with estimates for a range of ecosystem types (Moroni 2006). When these fall rates were applied to the CBM-CFS3, agreement between measured and modeled snag stem and branch C dynamics improved (Tables 6 and 7). All of the GOF statistics improved for the natural disturbance group of strata (Table 10). For the harvested group of strata, all of the GOF statistics improved except for the bias of the snag stem pool, which increased from 11% to 63% (Table 10). The impact of this bias on the modeled estimates of the total C budget for this study was small, however, because the snag stem C stocks in harvested stands were small, ranging from 0 to 1.1 Mg·ha^{-1} (Tables 6 and 7), relative to natural disturbances, where they ranged from 0.1 to 19.3 Mg·ha^{-1} (Tables 6 and 7).

Snag fall rates are a user-controlled model parameter that can be easily modified in the CBM-CFS3 to improve the model's representation of snag dynamics for an ecosystem similar to the one studied here. Results from this study also suggest that representation of the snag dynamics in the study sites could be further improved by selecting an appropriately shaped yield curve that accurately reflects the age of onset of senescence (fir in this study). The CBM-CFS3 uses an exponential decay curve for snag C commencing at the year of disturbance. However, Moroni et al. (2010) observed that snags measured in recently naturally disturbed strata (F/I/Y and S/B/Y) had not yet begun to collapse and transfer C to the woody debris pool. Therefore, at the finer scale, snag dynamics may be improved if the snag fall curve is represented as a sigmoidal curve with low snag fall up to 8 years after disturbance followed by a period of rapid snag fall, leaving few snags standing 15 years after disturbance (Bull 1983; Everett et al. 1999; Garber et al. 2005). This would produce modeled results consistent with the observations in this study, with fewer snags falling in the first 3 years following disturbance and fewer snags surviving ~15–30 years after disturbance. Tracking age cohorts of snags in each stand is, however, computationally more demanding, as it would greatly increase the amount of information simulated in each stand. Refining the representation of snag dynamics will likely impact estimates of snag and woody debris C at the site level but only have a minor impact on landscape-level estimates of snag C stocks. This is supported by the GOF statistics that show some bias in snag pool estimates when the data are grouped (Tables 9 and 10) but not for the data set as a whole (Table 8).

The differing impacts of disturbance history and temporal dynamics on woody debris C are captured by the CBM-CFS3 (Tables 6 and 7). Measured and modeled amounts of woody debris C increased following harvesting, and there was more woody debris C in recently harvested (F/H/Y and S/H/Y) than recently naturally disturbed strata (F/I/Y and S/B/Y). Measured and modeled woody debris C decreased in the three to four decades following harvesting (from F/H/Y to F/H/M and from S/H/Y to S/H/M) and was higher in middle-aged naturally disturbed strata (F/I/M and S/B/M) than in middle-aged harvested strata (F/H/M and S/H/M). In addition, the CBM-CFS3 modeled values for the woody debris C pool reflected low amounts of measured woody debris C in middle-aged harvested sites (F/H/M, F/HT/M, and S/H/M) (Tables 6 and 7).

The CBM-CFS3 estimated CWD C to be 4%–203% of measured CWD C at all but old fir (F/U/O) and old harvest-origin spruce strata (S/H/O) (Tables 6 and 7). As snags fall, they transfer C from snag pools (snag stems and snag branches) to woody debris pools (medium and aboveground fast excluding coarse roots). After natural disturbance, the CBM-CFS3 moved snag C to woody debris C following an exponential decay pattern commencing immediately following disturbance. The CBM-CFS3 is generating woody debris C from collapsing snags earlier than was encountered in the field, explaining the trend in field-measured estimates of woody debris C being below modeled estimates of woody debris C in recently naturally disturbed sites (F/Y/I and S/B/Y). Unadjusted CBM-CFS3 estimates of woody debris C generally ranked higher than measured woody debris C (Tables 6 and 7). Because snag dynamics influence woody debris dynamics by impacting the amount and timing of inputs of woody debris to the forest floor from collapsing snags, the impact of snag fall rates on modeled woody debris abundance was examined separately. Changing fall rates of snag stems from the default to 0.1 (10% fall·year^{-1}) and snag branches from the default to 0.2 (20% fall·year^{-1}) while leaving woody debris decay rates unchanged did not alter the trend of modeled woody debris C generally ranking above measured woody debris C (data not shown). This suggests that the decay rate for woody debris in the CBM-CFS3 may be underestimated for studied sites.

A range in basal decay rate values (greater than default values) for the medium (CWD) and aboveground fast (S&FWD) pools was tested and results are reported for the parameters producing the best GOF statistics. The altered basal decay rates at 10 °C are 0.06 for CWD and 0.28 for S&FWD that are about two times greater than default basal decay rates (CWD, 0.0374; S&FWD, 0.0145; recall that the applied decay rates in the model are lower because of the low MAT in the study sites) (Table 4). Increasing the basal decay rate for these woody debris pools generally increased model accuracy, the major exception being no improvement to the correlations for CWD in the fir group of strata, CWD in both disturbance groups of strata, and S&FWD in the harvest disturbance group of strata. We used the model's current Q_{10} relationships for these pools, the range in MATs for the study sites (1.7 to 4.4) (Table 2), and the adjusted basal decay rates to calculate the range in applied decay rates for comparison with values reported in the literature. The applied decay rates for CWD ranged from 0.021 to 0.0254, which are comparable with values reported for studies with comparable MATs by Foster and Lang (1982) (applied decay rate = 0.029) for balsam fir and Laiho and Prescott (1999) (applied decay rate = 0.0286) for subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). The applied decay rates for S&FWD based on the adjusted basal decay rate in this study ranged from 0.0807 to 0.0973. We could find only one relevant study on the decomposition rate of substrates that would be typical components of the S&FWD. Taylor et al. (1991) estimated a range in decay rates for cones, twigs, and branches of Engelmann spruce (*Picea engelmanii* Parry ex Engelm.) and subalpine fir to range from 0.0265 to 0.691. These values are lower than applied decay rate values based on the adjusted basal decay rate estimated in this study. The study of Taylor et al. (1991) was situated in the Rocky Mountains where MAT may be similar to that at our sites but mean annual precipitation much lower. It is possible that different moisture conditions between the Rocky Mountains (relatively dry) and Newfoundland boreal forests (relatively wet) could account for the difference in estimated decay rates. However, the decay dynamics of this pool have not been well documented and clearly require further study.

Applied decay rates can be modified in the model, not only by changing the basal decay rate but also the value for Q_{10} or the temperature sensitivity relationship itself. Currently, there is debate in the scientific literature over how the temperature sensitivity of soil organic matter decomposition should be expressed (Chen and Tian 2005; Tuomi et al. 2008; Fissore et al. 2009). Although this debate may be relevant to woody debris decomposition as well, insufficient research has been conducted on the temperature sensitivity of woody debris decomposition to justify altering the Q_{10} value or temperature sensitivity relationship for these pools in CBM-CFS3. Using the temperature sensitivity expression in the model and the default basal decay rates, we calculated that, in most cases, the Q_{10} would have to be dropped below 1 (which is biologically improbable) to arrive at the same applied decay rates based on the adjusted basal decay rate (this study). This result suggests that factors other than temperature sensitivity (as currently expressed in the model) may be influencing woody debris decay. Studies of woody decomposition have indicated that moisture content (or conversely aeration porosity) of woody material, decomposer and tree species, and size of woody material may be more important limiting factors to decomposition than temperature (Harmon et al. 2000; Progar et al. 2000). Indications are that there may be a moisture content (or aeration porosity) optimum for woody decay, as researchers have observed depressed dead wood decay rates under very low (Erickson et al. 1985) and high (Hagemann et al. 2010) moisture conditions.

Another reason that the size of modeled and measured woody debris pools do not agree well is that buried woody debris was likely underestimated in this study. Point sampling techniques like those used in this study would tend to underestimate buried wood stocks compared with the more labour-intensive trenching used by Hagemann et al. (2010) who found that significant amounts of small-diameter woody debris were buried in thick bryophyte layers (Hagemann et al. 2010). Thus, collectively, the results in this and other studies suggest that further research is required to improve our understanding of and ability to model the ecology and decay dynamics of woody debris and in particular the less well studied small-diameter woody debris in boreal forests where bryophytes are common and can bury and influence the decay dynamics of dead wood.

Conclusions

This study demonstrates the complexities, challenges, and benefits of comparing forest ecosystem C stock predictions and field measurements as recommended for Tier 3 models by the IPCC. Forest C stocks in Newfoundland boreal balsam fir and black spruce forests were measured in the field and compared with those modeled by the CBM-CFS3 in stands regenerating after the major natural and anthropogenic disturbances of the region. Agreement between field-measured and CBM-CFS3-modeled estimates of forest C stocks was good when results for all sites were combined, indicating that the CBM-CFS3 can be successfully applied to the forest types in this study and increases confidence in estimates from the CBM-CFS3 for other similar forest types in the boreal.

In this study, forest C pools were identified where estimation of stocks at finer scales could be improved with further calibration and benefit from new research. When comparing field-measured data with the CBM-CFS3-modeled data at the plot level, consequences of discrepancies between measured and modeled yield curves must be accounted for. To limit these discrepancies, yield curves must be carefully selected to be the most appropriate for sites, or sites must be carefully selected from the same population of forest types used to develop the yield curves. Our results indicate that snag fall rates for the forest types studied here should be higher than the default rate used in the CBM-CFS3 and that snag dynamics would likely be better represented by a sigmoidal decay curve rather than an exponential decay curve. Relatively high uncertainty for woody debris decay rates indicates that further research is required to better understand and quantify the ecology and decay dynamics of small-diameter CWD and S&FWD, especially as affected by interactions with thick bryophyte layers that are common in the boreal forests of Canada. The poor correlation between measured and modeled soil pools emphasizes the need to increase the quantity and quality of forest soil C estimates using powerful sampling designs to enable detection of trends and changes (Yanai et al. 2003; Shaw et al. 2008). The lack of temporal trends in soil C pools suggests that soil C stocks are equally or more influenced by site factors rather than site productivity or disturbance history.

New plot-level data for the boreal forest collected as part of Canada's new National Forest Inventory (Natural Resources Canada 2009) will be used to further test the modifications to the CBM-CFS3 recommended in this study. The National Forest Inventory ground plot data will provide opportunities to test these recommendations, contribute to our understanding of forest C dynamics, and improve our ability to model forest C stocks and stock changes with greater accuracy at the national scale. This emphasizes the need for a large number of total ecosystem C stock measurements in plots that represent a range of ecosystem types, disturbance histories, and climatic conditions to validate Tier 3 models, as recommended by the IPCC.

Acknowledgements

We thank the Model Forest of Newfoundland and Labrador for funding, Len Moores and Ivan Downton for logistical support, and Chris Callahan, Blaine Park, Harvey Thomas, Fraser Butt, Meril Lingard, Douglas Piercy, Dave Stone, Dave O'Brian, Brian McLaren, Wayne Brown, Kerry Hutchings, and Burt Anstey for help with site selection. Thanks to Michelle Anderson, Boyd Pittman, and Jim Gosse for help locating and typing aerial photographs. We thank the Newfoundland and Labrador Department of Natural Resources, Corner Brook Pulp and Paper, and AbitibiBowater for other support that enabled the completion of this project. Lastly, thanks to Caroline Simpson and anonymous referees for comments on earlier drafts of the manuscript.

References

Ahti, T., Hämet-Ahti, L., and Jalas, J. 1968. Vegetation zones and their sections in northwestern Europe. Ann. Bot. Fenn. **5**: 169–211.

Boudewyn, P., Song, X., Magnussen, S., and Gillis, M.D. 2007. Model-based, volume-to-biomass conversion for forested and vegetated land in Canada. Nat. Resour. Can. Can. For. Serv. Pac. For. Cent. Inf. Rep. BC-X-411.

Bull, E.L. 1983. Longevity of snags and their use by woodpeckers. *In* Proceedings of the Snag Habitat Management Symposium. *Edited by* J.W. Davis, G.A. Goodwin, and R.A., Ochenfels. U.S. For. Serv. Gen. Tech. Rep. RM-GTR-99. pp. 64–67.

Burns, R.M., and Honkala, B.M. (*Technical Coordinators*). 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. U.S. Dep. Agric. Agric. Handb. 654. Vol. 2. USDA Forest Service, Washington, D.C.

Canadell, J.G., Kirschbaum, M.U.F., Kurz, W.A., Sanz, M.-J., Schlamadinger, B., and Yamagata, Y. 2007. Factoring out natural and indirect human effects on terrestrial carbon sources and sinks. Environ. Sci. Policy, **10**(4): 370–384. doi:10.1016/j.envsci.2007.01.009.

Chen, H., and Tian, H.-Q. 2005. Does a general temperature-dependent Q_{10} model of soil respiration exist at biome and global scale? J. Integr. Plant Biol. **47**(11): 1288–1302. doi:10.1111/j.1744-7909.2005.00211.x.

Chen, W., Chen, J.M., and Cihlar, J. 2000. An integrated terrestrial ecosystem carbon-budget model based on changes in disturbance, climate and atmospheric chemistry. Ecol. Model. **135**(1): 55–79. doi:10.1016/S0304-3800(00)00371-9.

Chertov, O., Bhatti, J.S., Komarov, A., Mikhailov, A., and Bykhovets, S. 2009. Influence of climate change, fire and harvest on the carbon dynamics of black spruce in Central Canada. For. Ecol. Manag. **257**(3): 941–950. doi:10.1016/j.foreco.2008.10.038.

Clark, D.F., Kneeshaw, D.D., Burton, P.J., and Antos, J.A. 1998. Coarse woody debris in sub-boreal spruce forests of west-central British Columbia. Can. J. For. Res. **28**(2): 284–290. doi:10.1139/cjfr-28-2-284.

Ecoregions Working Group. 1989. Ecoclimatic regions of Canada: first approximation. Report and national map at 1 : 7 500 000 scale. Ecological Land Classification Series No. 23. Ecoregions Working Group, Canada Committee on Ecological Land Classification. Sustainable Development Branch, Canadian Wildlife Service, Conservation Protection, Environment Canada, Ottawa, Ont.

Erickson, H.E., Edmonds, R.L., and Peterson, C.E. 1985. Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems. Can. J. For. Res. **15**(5): 914–921. doi:10.1139/x85-147.

Everett, R., Lehmkuhl, J., Schellhaas, R., Ohlson, P., Keenum, D., Riesterer, H., and Spurbeck, D. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA. Int. J. Wildland Fire, **9**(4): 223–234. doi:10.1071/WF00011.

Fissore, C., Giardina, C.P., Swanston, C.W., King, G.M., and Kolka, R.K. 2009. Variable temperature sensitivity of soil organic carbon in North American forests. Glob. Change Biol. **15**(9): 2295–2310. doi:10.1111/j.1365-2486.2009.01903.x.

Foster, J.R., and Lang, G.E. 1982. Decomposition of red spruce and balsam fir boles in the White Mountains of New Hampshire. Can. J. For. Res. **12**(3): 617–626. doi:10.1139/x82-094.

Garber, S.M., Brown, J.P., Wilson, D.S., Maguire, D.A., and Heath, L.S. 2005. Snag longevity under alternative silvicultural regimes in mixed-species forests of central Maine. Can. J. For. Res. **35**(4): 787–796. doi:10.1139/x05-021.

Hagemann, U., Moroni, M.T., and Makeschin, F. 2009. Dead wood abundance in Labrador high-boreal black spruce forests. Can. J. For. Res. **39**(1): 131–142. doi:10.1139/X08-166.

Hagemann, U., Moroni, M.T., Gleißner, J., and Makeschin, F. 2010. Accumulation and preservation of dead wood upon burial by bryophytes. Ecosystems, **13**(4): 600–611. doi:10.1007/s10021-010-9343-4.

Hämet-Ahti, L., Ahti, T., and Koponen, T. 1974. A scheme of vegetation zones for Japan and adjacent regions. Ann. Bot. Fenn. **11**: 59–88.

Harmon, M.E., Krankina, O.N., and Sexton, J. 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. Can. J. For. Res. **30**(1): 76–84. doi:10.1139/cjfr-30-1-76.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr., and Cummins, K.W. 2004. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **34**: 59–234. doi:10.1016/S0065-2504(03)34002-4.

Intergovernmental Panel on Climate Change. 2003. 2003 good practice guidance for land use, land-use change and forestry. *Edited by* J. Penman et al. Institute for Global Environmental Strategies, Hayama. Available from www.ipcc-nggip.iges.or.jp.

Intergovernmental Panel on Climate Change. 2006. 2006 guidelines for national greenhouse gas inventories. *Edited by* S. Eggleston et al. Institute for Global Environmental Strategies, Hayama. Available from www.ipcc-nggip.iges.or.jp.

Kull, S.J., Kurz, W.A., Rampley, G.J., Banfield, G.E., Schivatcheva, R.K., and Apps, M.J. 2007. Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.0: users' guide. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta.

Kurz, W.A., and Apps, M.J. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. **9**(2): 526–547. doi:10.1890/1051-0761(1999)009[0526:AYRAOC]2.0.CO;2.

Kurz, W.A., and Apps, M.J. 2006. Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to meet the reporting requirements of the Kyoto Protocol. Mitig. Adapt. Strat. Glob. Change, **11**(1): 33–43. doi:10.1007/s11027-006-1006-6.

Kurz, W.A., Apps, M.J., Webb, T.M., and McNamee, P.J. 1992. Carbon Budget of the Canadian Forest Sector. Phase I. For. Can. North. For. Cent. Inf. Rep. NOR-X-326.

Kurz, W.A., Apps, M., Banfield, E., and Stinson, G. 2002. Forest carbon accounting at the operational scale. For. Chron. **78**: 672–679.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J. 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. **220**(4): 480–504. doi:10.1016/j.ecolmodel.2008.10.018.

Laiho, R., and Prescott, C.E. 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous forests. Can. J. For. Res. **29**(10): 1592–1603. doi:10.1139/cjfr-29-10-1592.

Li, Z., Kurz, W.A., Apps, M.J., and Beukema, S.J. 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. **33**(1): 126–136. doi:10.1139/x02-165.

McKenney, D.W., Kesteven, J.L., Hutchinson, M.F., and Venier, L. 2001. Canada's plant hardiness zones revisited using modern climate interpolation techniques. Can. J. Plant Sci. **81**(1): 139–143. doi:10.4141/P00-030.

Moroni, M.T. 2006. Disturbance history affects dead wood abundance in Newfoundland boreal forests. Can. J. For. Res. **36**(12): 3194–3208. doi:10.1139/X06-195.

Moroni, M.T., Shaw, C.H., and Otahal, P. 2010. Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin I: field study. Can. J. For. Res. **40**(11): 2135–2145. doi:10.1139/X10-154.

Natural Resources Canada. 2009. Canada's National Forest Inventory. Online database. Available from nfi.nfis.org/ [accessed April 2009].

Progar, R.A., Schowalter, T.D., Freitag, C.M., and Morrell, J.J. 2000. Respiration from coarse woody debris as affected by moisture and saprotroph functional diversity in Western Oregon. Oecologia (Berl.), **124**(3): 426–431. doi:10.1007/PL00008868.

Shaw, C.E., Boyle, J.R., and Omule, A.Y. 2008. Estimating forest soil carbon and nitrogen stocks with double sampling for stratification. Soil Sci. Soc. Am. J. **72**(6): 1611–1620. doi:10.2136/sssaj2007.0219.

Smith, C.Y., Moroni, M.T., and Warkentin, I.G. 2009. Snag dynamics in post-harvest landscapes of western Newfoundland balsam-fir dominated boreal forests. For. Ecol. Manag. **258**(5): 832–839. doi:10.1016/j.foreco.2009.03.027.

Smith, J., and Smith, P. 2007. Introduction to environmental modelling. Oxford University Press Inc., New York.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., and Whitmore, A.P. 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma, **81**(1–2): 153–225. doi:10.1016/S0016-7061(97)00087-6.

Soil Classification Working Group. 1998. The Canadian system of soil classification. Agric. Agri-Food Can. Publ. 1646 (revised). NRC Research Press, Ottawa, Ont.

Taylor, B.R., Prescott, C.E., Parsons, W.J.F., and Parkinson, D. 1991. Substrate control of litter decomposition in four Rocky Mountain coniferous forests. Can. J. Bot. **69**(10): 2242–2250. doi:10.1139/b91-281.

Tuomi, M., Vanhala, P., Karhu, K., Fritze, H., and Liski, J. 2008. Heterotrophic soil respiration — comparison of different models describing temperature dependency. Ecol. Model. **211**(1–2): 182–190. doi:10.1016/j.ecolmodel.2007.09.003.

United Nations Framework Convention on Climate Change. 2009. unfccc.int/2860.php [accessed April 2009].

Whitmore, A.P. 1991. A method for assessing the goodness of computer simulation of soil processes. J. Soil Sci. **42**(2): 289–299. doi:10.1111/j.1365-2389.1991.tb00410.x.

Yanai, R.D., Stehman, S.V., Arthur, M.A., Prescott, C.E., Friedland, A.J., Siccama, T.G., and Binkley, D. 2003. Detecting change in forest floor carbon. Soil Sci. Soc. Am. J. **67**(5): 1583–1593. doi:10.2136/sssaj2003.1583.

Zielonka, T., and Niklasson, M. 2001. Dynamics of dead wood and regeneration pattern in natural spruce forest in the Tatra Mountains, Poland. Ecol. Bull. **49**: 159–163.