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CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards

W.A. Kurz[a,*], C.C. Dymond[a], T.M. White[a], G. Stinson[a], C.H. Shaw[b], G.J. Rampley[a], C. Smyth[a], B.N. Simpson[b], E.T. Neilson[a], J.A. Trofymow[a], J. Metsaranta[a], M.J. Apps[a]

[a] Natural Resources Canada, Canadian Forest Service, Carbon Accounting Team, 506 West Burnside Road, Victoria, BC, Canada V8Z 1M5
[b] Natural Resources Canada, Canadian Forest Service, Carbon Accounting Team, 5320 122nd Street, Edmonton, AB, Canada T6H 3S5

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ABSTRACT

The scientific community, forest managers, environmental organizations, carbon-offset trading systems and policy-makers require tools to account for forest carbon stocks and carbon stock changes. In this paper we describe updates to the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) implemented over the past years. This model of carbon-dynamics implements a Tier 3 approach of the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for reporting on carbon stocks and carbon stock changes resulting from Land Use, Land-use Change and Forestry (LULUCF). The CBM-CFS3 is a generic modelling framework that can be applied at the stand, landscape and national levels. The model provides a spatially referenced, hierarchical system for integrating datasets originating from different forest inventory and monitoring programs and includes a structure that allows for tracking of land areas by different land-use and land-use change classes. Ecosystem pools in CBM-CFS3 can be easily mapped to IPCC-defined pools and validated against field measurements. The model uses sophisticated algorithms for converting volume to biomass and explicitly simulates individual annual disturbance events (natural and anthropogenic). Several important scientific updates have been made to improve the representation of ecosystem structure and processes from previous versions of CBM-CFS. These include: (1) an expanded representation of dead organic matter and soil carbon, particularly standing dead trees, and a new algorithm for initializing these pools prior to simulation, (2) a change in the input data requirement for simulating growth from biomass to readily available merchantable volume curves, and new algorithms for converting volume to biomass, (3) improved prediction of belowground biomass, and (4) improved parameters for soil organic matter decay, fire, insect disturbances, and forest management. In addition, an operational-scale version of CBM-CFS3 is freely available and includes tools to import data in standard formats, including the output of several timber supply models that are commonly used in Canada. Although developed for Canadian forests, the flexible nature of the model has enabled it to be adapted for use in several other countries.

* *Corresponding author*. Tel.: +1 250 363 6031; fax: +1 250 363 0775.
E-mail address: Werner.Kurz@nrcan.gc.ca (W.A. Kurz).
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1. Introduction

Forests play an important role in the global carbon (C) cycle (Denman et al., 2007). As countries seek to understand and influence the trajectory of global change, they will require a sound understanding of forest C dynamics. Specifically, forest managers, policy-makers, and governments require the means to quantify past forest C stocks and stock changes, and to explore future forest and land-use policy options. Tools developed to meet these needs typically involve a significant modelling component for generating estimates of C stocks and stock changes for large landscapes, as it would not be cost-effective to obtain these through measurements alone. Modelling is also the only means available to simulate future conditions. Forest ecosystems are heterogeneous, so there will never be enough field measurements to characterize all forests under all conditions (Running et al., 1999). Knowledge gained from detailed field measurements in specific ecosystems can however, be used to develop, validate, and calibrate models that are applied in larger landscape analyses. This is the standard approach to wood supply analyses practiced by forest management agencies for decades. Our efforts extend current practices from merchantable volume to ecosystem carbon stocks and explicitly take natural disturbances into account.

International agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Montreal Process require countries to monitor and report on forest C stocks or stock changes. Guidance is available for the development of monitoring programs through the internationally agreed upon methodology produced by the Intergovernmental Panel on Climate Change (IPCC)—the Good Practice Guidance (GPG) for Land Use, Land-use Change and Forestry (LULUCF) (IPCC, 2003). The GPG recommends methods for reducing uncertainty in estimates of forest C stocks, stock changes, and greenhouse gas (GHG) emissions from forests. The GPG describes how to estimate these dynamics in a way that is complete, consistent over time, comparable among regions, subject to quality control and assurance, and reflecting regional circumstances and practicalities for implementation. The GPG provides users with three methodological tiers that progress from least (Tier 1) to greatest (Tier 3) degree of estimation certainty.

Two methods for estimating forest C stock changes meet the Tier 3 guidelines. One is the "inventory change" method, which involves calculating the difference between two detailed inventories at different points in time (IPCC, 2003). A suite of models (e.g. FORCARB, Heath and Birdsey, 1993) can calculate C stocks (also called a C inventory) from forest inventories. This can be a very accurate method of estimating total C stock change because it integrates all relevant factors (natural disturbances, management, land-use change and climate). However, this method does not provide estimates of inter-annual variation within the observation period. Additional data are required to estimate non-CO_2 emissions (i.e. CH_4, N_2O) from fires and to report land-use change impacts. Moreover, the approach is further complicated when the inventories are based on field measurements collected in a fraction of all inventory plots each year. The second method suggested by the GPG is the "one inventory plus change" method. This requires a forest and land inventory; data such as changes in land-use, forest management activities, natural disturbances; and detailed models (e.g. for estimating growth rates, decomposition and non-CO_2 emissions). Because of the flexibility offered by models, the inventory need not have been created at the beginning of the period of interest, provided the data are available to adjust the inventory to the start year of the analysis.

In this paper, we describe the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 v1.1) and its implementation of the Tier 3 GPG standard. The model serves both as the core component of Canada's National Forest C Monitoring Accounting Reporting System (NFCMARS) (Kurz and Apps, 2006) and meets the C accounting needs of operational foresters in Canada (Kurz et al., 2002; Kull et al., 2006). Canada's NFCMARS uses the "one inventory plus change" method, with the CBM-CFS3 calculating annual changes caused by ecological processes and human activities. This approach was adopted because Canada does not currently have two successive national inventories from which to calculate change, and because it allows quantification of annual C-impacts by different causal agents such as natural vs. human-caused disturbances. Moreover, the model can be used for analyses of future forest C balances to assess policy and management alternatives (Kurz et al., 2008b).

Here, we briefly summarize models of forest C-dynamics and discuss where CBM-CFS3 fits in the larger context of systems ecology. We also describe the structure and parameters of the CBM-CFS3, emphasizing what has been validated or changed from previous descriptions of the model (Kurz et al., 1992; Kurz and Apps, 1999), including the representation of land area in the model, biomass and dead organic matter (DOM) dynamics, the simulation of disturbances such as forest management activities, land-use change, and natural events like fire or insect outbreaks. We describe how the CBM-CFS3 outputs link with other research and monitoring efforts and lastly, we discuss model applications. To illustrate model behaviour, we present examples of stand and landscape simulations using a typical pine forest in western Canada.

1.1. *Approaches to modelling forest C dynamics*

Models of forest C dynamics are usually grouped into those where growth is driven by empirical yield curves (e.g. EFISCEN, Nabuurs et al., 2000; CO2FIX, Masera et al., 2003) and those where growth is driven by simulating photosynthesis (e.g. 3-PG, Landsberg and Waring, 1997; BIOME-BGC, Running and Gower, 1991; CENTURY, Metherall et al., 1993; TEM, Tian et al., 1999). Both types of models are valuable for different applications. Photosynthesis-driven models require input datasets such as leaf-area index (e.g. Running and Gower, 1991), climate variables, and soil variables (e.g. McGuire et al., 2002), at time steps ranging from hourly to monthly.

Empirical yield data driven models are powered by the same data that operational foresters use in timber supply analysis and forest management planning tools. These models require data on merchantable wood volume as a function of stand type and age. An application that yield-driven models are particularly well suited for is the explicit simulation of human activities and natural disturbances. These models simulate growth based on past observations, however, and therefore cannot, at this time, take into account global change factors, such as increasing atmospheric CO_2 concentrations or climate change. Photosynthesis-driven models, on the other hand, can currently simulate the response of the forest ecosystem to global change factors. These models are also particularly useful for modelling ecosystem dynamics for which detailed empirical yield data have not been compiled or are not available.

The CBM-CFS3 is a yield data driven model with explicit simulation of dead organic matter (DOM) dynamics. It simulates the C dynamics of above- and belowground biomass and DOM, including soils, and can represent both stand- and landscape-level forest dynamics. As a forest C accounting framework, it tracks C stocks, transfers between pools, and emissions of carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) (Fig. 1). The original CBM-CFS (Kurz et al., 1992) and CBM-CFS2 (Kurz and Apps, 1999) quantified the contribution of Canadian forest ecosystems and forestry activities to the global C budget. There have been various improvements and extensions, for example, accounting of forest products (Apps et al., 1999; Kurz et al., 2002). In the

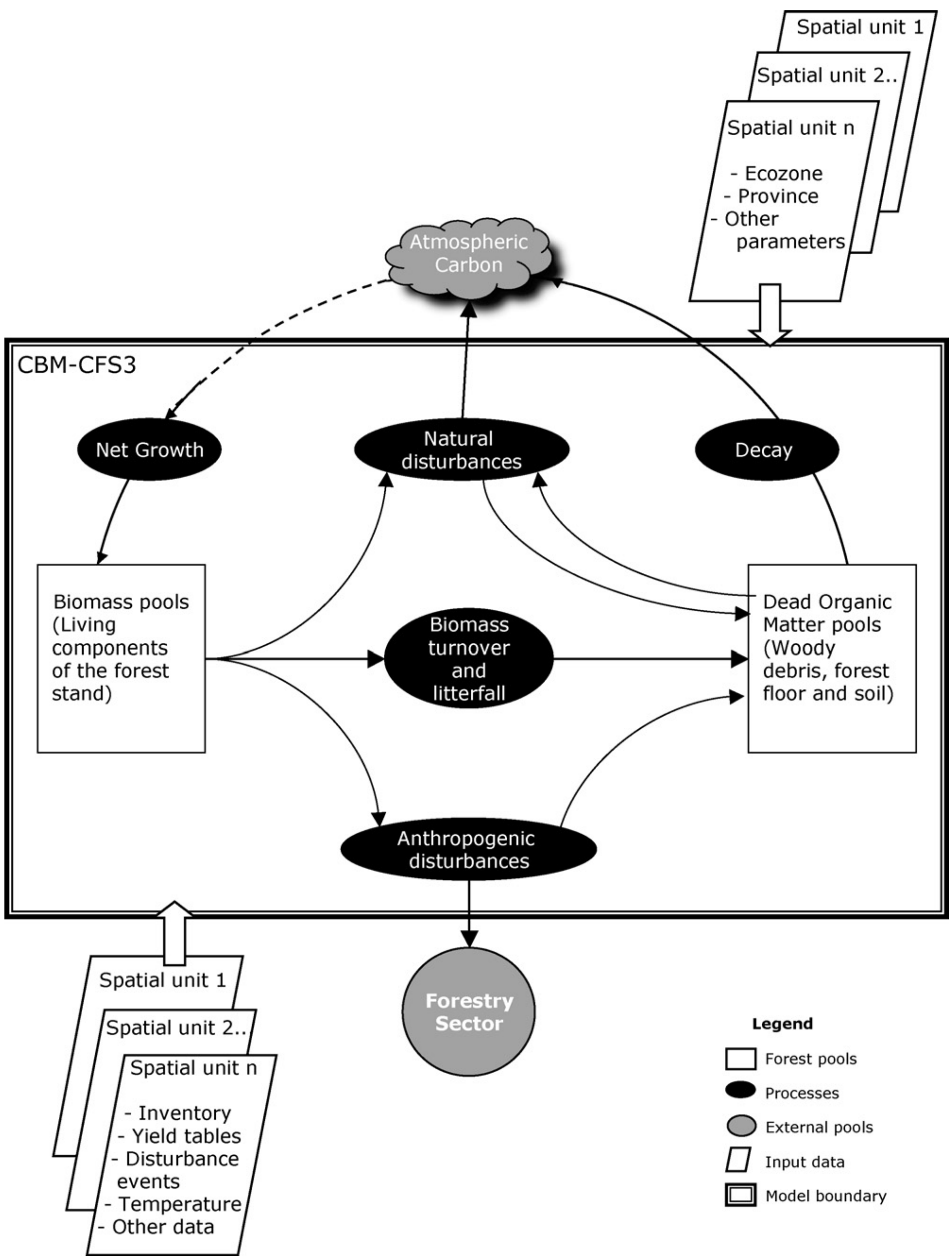

Fig. 1 – Simple schematic of CBM-CFS3. Simulation of growth causes carbon to enter the forest ecosystem as living biomass. Simulation of turnover and disturbance processes causes the transfers of carbon from biomass to DOM pools. Natural disturbances can cause the loss of carbon from the ecosystem as gaseous emissions (e.g. in the smoke from a forest fire). Harvesting causes the loss of carbon from the ecosystem to the forestry sector. Carbon is also lost from the ecosystem due to decay of the DOM and soil organic C.

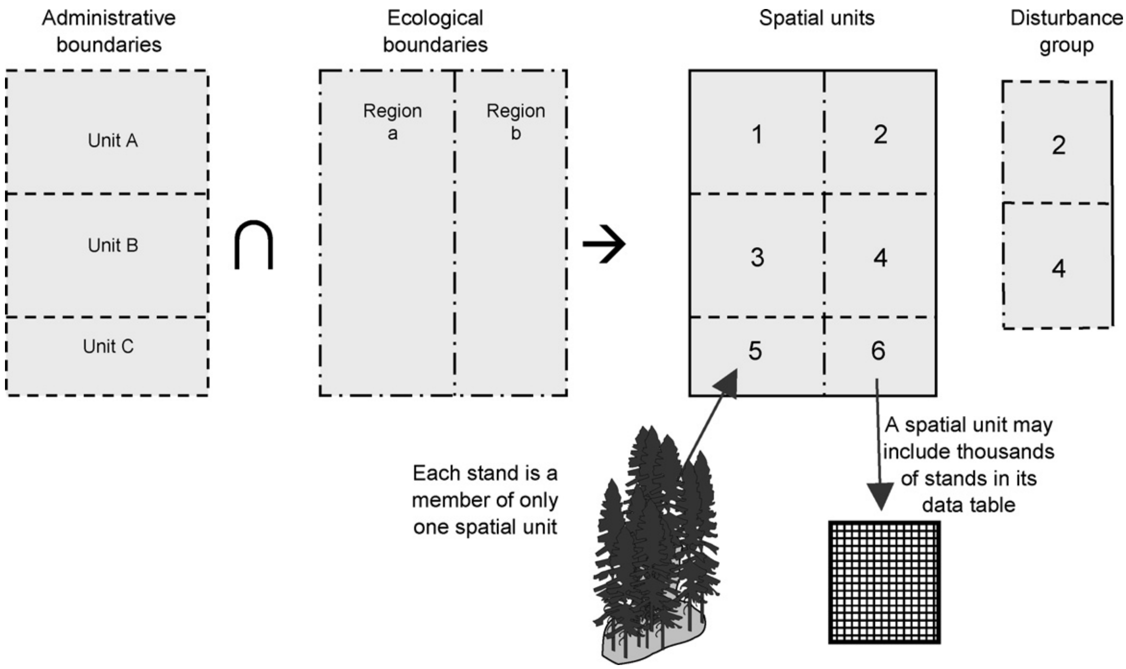

Fig. 2 – A hypothetical forest landscape comprised of administrative regions (A–C) and ecological regions (a) and (b) that are represented in CBM-CFS3 by spatial analysis units (1) through (6). Each forest stand in the study area landscape is spatially referenced to the spatial unit in which it is located, but its exact location is not stored in the model. Disturbance events can target stands within a spatial unit or group of spatial units (disturbance group). All input data and parameters are referenced to individual spatial units, or to groups of spatial units.

early stages of the development of the CBM-CFS models, forest C dynamics were of limited interest beyond academic and senior forest policy circles. Today, this is no longer the case. Most forest certification programs consider the contribution of a forest to the global C cycle to be an important indicator of the sustainability of management practices undertaken on a forest estate (e.g. Forest Stewardship Council, 2004). More importantly, international agreements (UNFCCC, Kyoto Protocol) require countries to monitor and report on forest C stocks or stock changes. Policy demands for the ability to project and estimate future C stock changes are also increasing. A new version of the model was needed to meet increasing requirements. The revised model was designed to meet the standards described in the GPG (IPCC, 2003). It serves as the core component of NFCMARS (Kurz and Apps, 2006), to provide policy-support (Kurz et al., 2008b) and as a tool that meets the C accounting needs of operational foresters in Canada (Kurz et al., 2002; Kull et al., 2006).

2. Representation of land areas

One challenge faced by landscape-level models is the integration of information about processes that operate at different spatial scales or are described by datasets that may vary in resolution. To meet this challenge, we designed the CBM-CFS3 as a generic framework to represent land areas and to allow for the integration of input data into a single spatial referencing framework.

Forest landscapes are typically comprised of large numbers of forest stands—communities of trees that are homogeneous enough to be treated as a unit. In the CBM-CFS3 modelling framework, the landscape is represented as a collection of spatial units (Fig. 2). Each stand in the study area is spatially referenced to the spatial unit in which it is located. For simplicity, we refer to unique areas of land within a spatial unit as stands, whether they are treed or not. Moreover, CBM-CFS3 tracks the GPG land-use class for each stand, e.g. managed forest land, or forest converted to cropland (IPCC, 2003).

Classifiers reference all input data and modelling parameters to individual spatial units or to groups of spatial units. For example, a harvest allocation can be assigned to the disturbance group of spatial units (2 and 4) that represent an administrative entity (Fig. 2). Meanwhile, a modelling parameter calibrated for ecological region (a) can be assigned in the model to the group of spatial units (1, 3 and 5) that belong to (a). Spatial units can be grouped into different configurations for different types of input data. This spatial referencing framework provides a structure into which data of different scales, or from different spatial referencing systems, can be integrated and allows scaling from local level to the landscape level at scales ranging from forest management units (typically 10^5 ha), provinces or regions (typically 10^7 ha), or all of Canada's managed forest lands (3×10^8 ha) without introducing scale-dependant artifacts. The CBM-CFS3 spatial framework is compatible with both GPG-recommended methods for representing land areas (IPCC, 2003).

The topology, or spatial relationship, between these units (e.g. adjacency) is not maintained by the model. The frame-

Table 1 – Spatial scale of default parameters provided with CBM-CFS3. The user can modify any of these parameters.

Parameter	Province or territory intersected with ecozone	Province or territory	Ecozone	Canada
Merchantability criteria definition		✓		
Species-level biomass coefficients	✓			
Genus-level biomass coefficients	✓			
Forest type biomass coefficients	✓			
Fire impacts			✓	
Insect impacts	✓			
Harvest impacts		✓		
Deforestation impacts			✓	
DOM initialization assumptions	✓			
Foliage turnover rate (SW or HW)			✓	
Other wood turnover rates (SW or HW)			✓	
Merchantable stemwood turnover rate (SW or HW)			✓	
Coarse root turnover rate				✓
Fine root turnover rate				✓
Snag stems transfer rate (SW or HW)				✓
Snag branches transfer rate (SW or HW)				✓
Base organic matter decay rate				✓
Q10 relationship between decay rates and temperature				✓
Proportion of decay to atmosphere				✓
Aboveground slow transfer rate				✓
Initial soil stocks for land that will be afforested			✓	

work provides the flexibility to design whatever system of spatial units is best suited to the study area of interest and to the available input data. If spatial operations are required to reference input data into the spatial units, these operations must be carried out in a geographic information system or other computing environment prior to loading the data into the model.

Each stand is described by area (ha), age, land class (e.g. managed forest land or forest converted to cropland, IPCC, 2003) and up to 10 classifiers. Classifiers are defined by the model user and typically describe characteristics of the land area such as site productivity, ownership, or leading species. Combinations of classifier values link stands with yield tables as described in Section 3.2. They are also useful in selecting stands for disturbances, as described in Section 4.1.

Within the CBM-CFS3 we provide default modelling parameters for Canada at nationally relevant administrative (provincial and territorial boundaries) and ecological (Ecological Stratification Working Group, 1996) scales (Table 1, Box 1). The administrative boundaries affect the merchantability criteria definition used by the model during the simulation of biomass dynamics and the calculation of harvest impacts. The ecological units capture large-scale variability in growth, decomposition, tree allometry, forest composition, disturbances, etc. These parameters are provided for convenience. To use the default parameter values a study area's spatial units must be referenced to the appropriate province or territory and ecozone. Users can modify parameter values through a graphical user interface to better represent their site-specific or country-specific values.

3. Biomass and decay dynamics

The CBM-CFS3 simulates annual changes in each stand's C stocks of each pool that occur due to growth, biomass turnover, litterfall, transfer and decomposition (Fig. 3). The CBM-CFS3 also simulates complex disturbances that can alter biomass turnover, and transfers between DOM pools (litter, dead wood and soil) (see Section 4.2 on Disturbance Impacts). This section describes simulation of C dynamics over the course of stand development in the absence of disturbances, i.e. these dynamics occur in each stand in each year (see Box 1, Step 7).

3.1. *Pools*

The CBM-CFS3 tracks 10 biomass and 11 DOM C pools (Table 2). The living biomass pools are tracked separately for hardwood and softwoods within each stand using the following categories: merchantable stemwood, other wood, foliage, coarse roots and fine roots. The DOM pools are categorized by the type of material they contain and by their anticipated rate of decay.

The representation of DOM dynamics in CBM-CFS3 is more detailed than in CBM-CFS2 with the addition of pools to represent snags (standing dead trees) and the separation of DOM pools into aboveground (woody litter and organic soil horizons) and belowground (mineral soil horizons) components (Fig. 3). The addition of these pools provides the structure to more accurately reflect the different C dynamics between coarse woody debris (CWD) that is lying on the ground and standing dead trees, as well as the impacts of disturbances on different DOM pools. The two snag DOM pools (dead standing stems and branches) are tracked separately for hardwood and softwood species. Whether C originates from hardwood or softwood species is not tracked for the remaining seven pools that are distinguished by the type of biomass inputs, their relative decay rates (slow to very fast), and whether they occur above the mineral soil surface (aboveground) or below it (belowground). Throughout this paper, we refer to DOM pools as the system of pools used in CBM-

Box 1: Overview providing sequence of actions by CBM-CFS3 v1.1

(A) Steps Prior to a Simulation

(1) Run quality control check on input data.
(2) Load input data from MS-Access database to executable.
(3) Convert merchantable volume yield tables into C increment tables that provide biomass C increments for each biomass pool, referenced to stand age.

(B) Steps During Simulation Initialization

(4) Populate each inventory record with its classifiers and age, and initialize biomass and DOM C stocks.
  (a) Start with empty C pools at age 0,
  (b) Calculate biomass and DOM dynamics for *n* years (where *n* is the regional average natural disturbance return interval),
    (i) For each annual time step
      - Look up appropriate aboveground biomass increments and add to current aboveground biomass pools
      - Calculate belowground biomass C as a function of aboveground biomass
      - Calculate biomass turnover and add this C to the appropriate DOM pools. If biomass net increment is negative, then add this amount to turnover
      - Calculate decay rates (applying modifiers to base decay rates)
      - Calculate transfers between DOM pools and release to atmosphere
  (c) Disturb by wildfire (or other stand-replacing disturbance),
  (d) Determine total slow C at the end of an initialization cycle,
  (e) Compare total slow C with values at end of previous cycle,
  (f) If the slow DOM pools have not yet stabilized (>1% change) then keep the values at the end of the cycle, reset age to 0 and go back to (b).
(5) Once the slow pools have stabilized and a minimum of 10 iterations have been run, keep the DOM values at the end of the cycle, disturb using designated stand-initiating disturbance type and then grow the record to its age in the inventory. Populate biomass and DOM C pools with the resulting values.

(C) Steps During a Simulation

(6) For each year, apply disturbances.
  (a) For each disturbance event,
    (i) Apply disturbance controls
      - Select records until the target to disturb is met,
    (ii) Apply land-use classification changes (where applicable),
    (iii) Transfer carbon between pools using the specified disturbance matrix,
    (iv) Append future growth multipliers resulting from disturbance (where applicable),
    (v) Adjust stand age as appropriate for the type of disturbance,
    (vi) Apply transition rules (where applicable).
(7) For each year and inventory record, apply biomass and DOM dynamics.
  (a) Apply land-use classification changes for afforested or deforested stands 20 years after the original disturbance,
  (b) Look up appropriate aboveground biomass increments from Step 3 and add to current aboveground biomass pools,
  (c) Calculate belowground biomass C as a function of aboveground biomass,
  (d) Calculate biomass turnover and add this C to the appropriate DOM pools using litterfall turnover rates. If biomass net increment is negative, then add this amount to turnover,
  (e) Calculate decay rates (applying modifiers to base decay rates),
  (f) Calculate transfers between DOM pools and release to atmosphere.
(8) Run internal QC check on simulation.

(D) Steps After a Simulation

(9) Provide output in user-friendly format.
  (a) Summarize fluxes and stocks by time step, pools, disturbance types, land-use class and classifiers,
  (b) Load output into MS-Access database,
  (c) User can view results through pre-defined or customizable graphs and tables.

CFS3 to represent both dead organic matter and soil organic carbon.

The CBM-CFS3 pools can be easily aggregated into the IPCC pools for reporting purposes (Table 2). The resolution used in CBM-CFS3 (21 pools) is finer than the five pools used by the IPCC, and allows for enhanced representation of key ecological processes and comparison of predictions with field measurements. Prior to 2003, IPCC guidelines allowed one inventory for

Table 2 – Correspondence between pools in the Carbon Budget Model of the Canadian Forest Sector 3—version 1.1 (CBM-CFS3) and recommended pools by the Intergovernmental Panel on Climate Change Good Practice Guidance (GPG) (IPCC, 2003). SW = softwood, HW = hardwood, DOM = dead organic matter.

CBM-CFS3 pool	Description	GPG pool
Merchantable + bark (SW or HW)	Live stemwood of merchantable size[a] plus bark	Aboveground biomass
Other wood + bark (SW or HW)	Live branches, stumps and small trees including bark	Aboveground biomass
Foliage (SW or HW)	Live foliage	Aboveground biomass
Fine roots (SW or HW)	Live roots, approximately <5 mm diameter	Belowground biomass
Coarse roots (SW or HW)	Live roots, approximately ≥5 mm diameter	Belowground biomass
Snag stems DOM (SW or HW)	Dead standing stemwood of merchantable size including bark	Dead wood
Snag branches DOM (SW or HW)	Dead branches, stumps and small trees including bark	Dead wood
Medium DOM	Coarse woody debris on the ground	Dead wood
Aboveground fast DOM	Fine and small woody debris plus dead coarse roots in the forest floor, approximately ≥5 and <75 mm diameter	Litter
Aboveground very fast DOM	The L horizon[b] comprised of foliar litter plus dead fine roots, approximately <5 mm diameter	Litter
Aboveground slow DOM	F, H and O horizons[b]	Litter
Belowground fast DOM	Dead coarse roots in the mineral soil, approximately ≥5 diameter	Dead wood
Belowground very fast DOM	Dead fine roots in the mineral soil, approximately <5 mm diameter	Soil organic matter
Belowground slow DOM	Humified organic matter in the mineral soil	Soil organic matter

[a] Definition of merchantable size dimensions are model parameters, see Table 3.
[b] Soil Classification Working Group (1998).

biomass and a separate inventory for soils (IPCC, 1997). However, this led to an undesirable disconnect between biomass and DOM dynamics that was identified and rectified in subsequent guidelines (IPCC, 2003, 2006). Currently the simplest form of international reporting (Tier 1) assumes litter and soil organic matter C stocks are stable when forests remain as forests, but the design of the CBM-CFS3 is consistent with the more complex Tier 3 approach described by the IPCC that requires explicit links between biomass and DOM dynamics (IPCC, 2003).

The CBM-CFS3 is designed for forested upland sites resulting in a higher degree of uncertainty in C stocks and emissions estimation for poorly drained sites and sites with permafrost. Although peatlands are a significant component of the C budget in Canadian forests (Tarnocai, 2006) the peat component is not explicitly represented in the CBM-CFS3. This is due, in part, to the paucity of national data needed for parameterization (Yu et al., 2001). Pyrogenic C is another component of the forest C cycle garnering considerable interest in pedology; however, significant data gaps prevent parameterization of the CBM-CFS3 for this typically small pool (Preston and Schmidt, 2006).

3.2. *Growth*

Forest management agencies and industry have built up large libraries of yield tables to describe the accumulation of volume in the merchantable portion of tree stems as a function of stand age. To enable the use of these data sources, CBM-CFS2 was modified from using biomass over age to CBM-CFS3, that uses merchantable volume over age data to simulate growth. The yield tables are associated with forest stands inside the CBM-CFS3 using classifier values (such as genus and site-class), similar to the approach in many timber supply analysis models. The model assumes that the values reported in the yield tables represent gross merchantable wood volume (including decay, waste and breakage), except in British Columbia where it assumes yield table values represent net merchantable wood volume (Power and Gillis, 2006). Note that stand volumes reported in the inventory are not used to estimate growth, only the age from the inventory and the volume from the yield table is used.

While typical yield tables are in units of merchantable volume, estimates of C in all components of the stand are required to represent the C dynamics. The CBM-CFS3 uses equations developed by Boudewyn et al. (2007) to estimate aboveground biomass from the yield tables provided as model input. We used this approach because these volume-to-biomass equations are comprehensive—models were developed for all forest stand types found in Canada and require as input only information commonly available in typical Canadian forest inventory datasets. The development of the models relied on the availability of a large number of permanent and temporary sample plots (over 133,000) containing individual tree measurements (Boudewyn et al., 2007). Plots came from all provinces and territories in Canada except the Northwest Territories and Nunavut, with most from Quebec, about 15% from B.C. and the rest from the remaining jurisdictions. The plots represented 10 of the 12 ecozones in Canada that contain forests. The result of the work by Boudewyn et al. (2007) was about 270

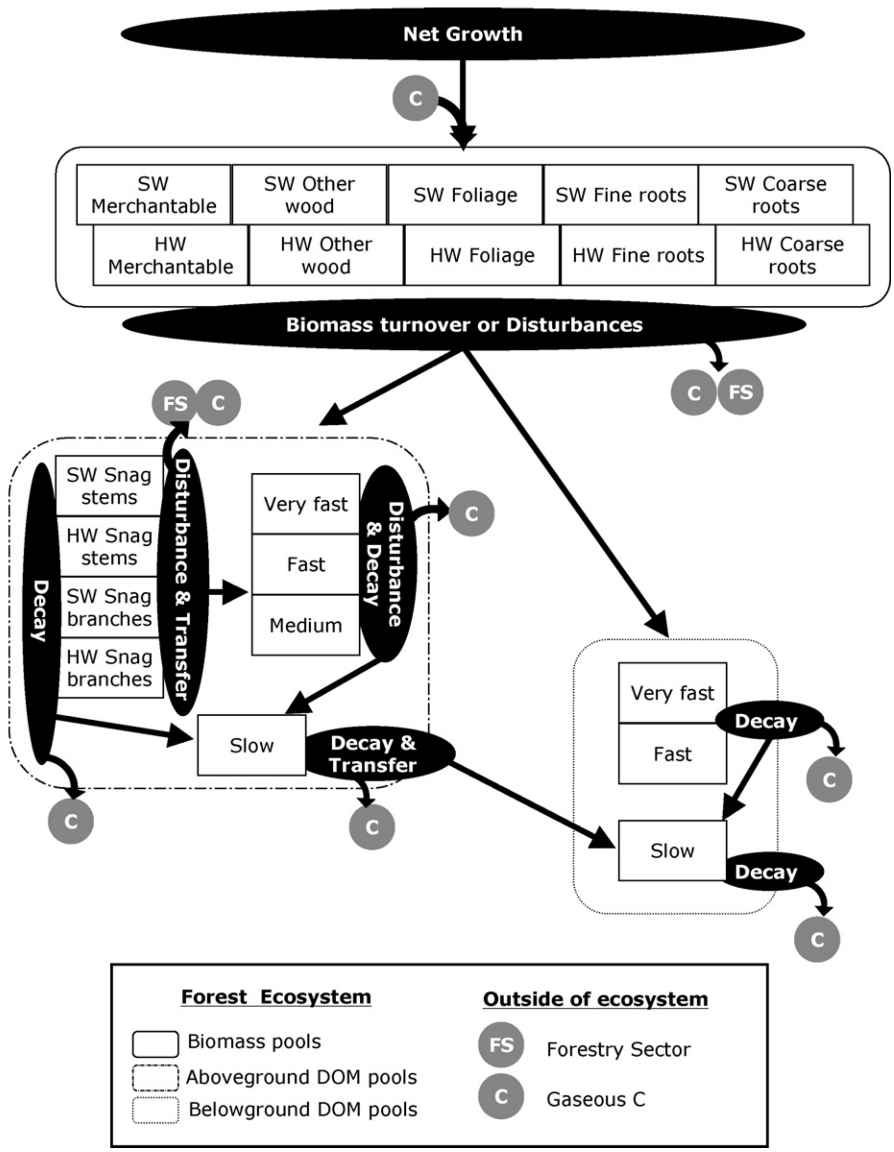

Fig. 3 – Conceptual design of CBM-CFS3. Simulation of growth causes carbon to enter the forest ecosystem and it is distributed among 10 different biomass pools. Simulation of turnover and disturbance processes causes the transfers of carbon from biomass to DOM pools. Disturbances can also cause the loss of carbon from the ecosystem as gaseous emissions or to the forestry sector. Carbon is transferred between DOM pools by a variety of mechanisms: decay, transfer and disturbance. Carbon that remains in the ecosystem eventually ends up in the belowground slow DOM pool. In the diagram, rectangles represent pools, rounded-rectangles represent groups of pools, arrows represent the movement of C between groups of pools, ovals represent the simulated processes and circles represent losses from the ecosystem. SW = softwood, HW = hardwood.

unique sets of model parameters to convert stand-level volume to aboveground biomass components for over 60 tree species.

The development of the stand-level volume-to-biomass models relied on the strong relationship between stand volume and stand biomass. First, individual tree biomass equations were drawn from the literature, with preference given to equations developed by Lambert et al. (2005), and used to estimate the biomass of individual tree components as a function of diameter at breast height and tree height. Individual tree biomass components and volume estimates were then summed into per hectare plot totals. Plots were stratified by province/territory, ecozone, leading species, predominant genus, and forest type, following the stratification system used in Canada's National Forest Inventory (CanFI2001, Power and Gillis, 2006). In addition to the biomass in merchantable-sized trees, expansion factors were developed to quantify the stemwood biomass for non-merchantable and sapling size trees. Further models were developed to calculate the proportions of total tree biomass found in stem wood, stem bark, branches and foliage. Boudewyn et al. (2007) describe the model fitting procedures used and provide all equations and parameter values.

The CBM-CFS3 estimates growth in C increments in preparation for a simulation (see Box 1, Step 3). The procedure starts with the softwood and hardwood merchantable volume from the yield tables being converted to biomass in units of dry-matter using the appropriate volume-to-biomass models (Fig. 4). Stemwood and stem bark biomass is split and the model assigns the merchantable portion to the "merchantable + bark" pool. The tops and stumps portion of the stemwood and stem bark are assigned to the "other wood + bark" pool. The CBM-CFS3 also assigns the stemwood and bark biomass for non-merchantable, saplings and all branches to the other wood pool. Foliage remains in a separate pool. The CBM-CFS3 converts units of dry matter to mass of C using a conversion factor of 0.5 g C/g dry matter (Matthews, 1993; Lamlom and Savidge, 2003). The annual change in C stock from one age to the next is saved in the growth increment array. Once the aboveground C increment is calculated, the CBM-CFS3 then calculates the belowground biomass and C increment using equations from Li et al. (2003). All equations used by the CBM-CFS3 are for stand-level biomass estimation. For single-species stands, the conversion procedure simply uses the volume to biomass conversion model appropriate for a given species, ecozone, and province. However, because the volume to biomass models are designed to single-species stands, an additional procedure was required to calculate the biomass for each component for mixed-species stands. For example, a mixed-species stand in a given ecozone and province with 100 m^3 of merchantable volume, 60 m^3 of which was softwood and 40 m^3 of which was hardwood, the biomass estimate for the softwood component would be obtained by converting 100 m^3 of merchantable volume to biomass using the equations appropriate to the softwood species and multiplying this value by 0.6. Similarly, the biomass estimate for the hardwood component would be obtained by converting 100 m^3 of merchantable volume to biomass using the equations appropriate to the hardwood species and multiplying this value by 0.4. The values 0.6 and 0.4 are the proportions of merchantable volume for the softwood and hardwood components, respectively.

The CBM-CFS3 uses merchantability criteria to partition the biomass from stemwood into tops, stumps and merchantable stemwood pools (values are available to model users when they download the model). Presently, these proportions are derived using general hardwood and softwood taper equations (Alemdag, 1982, 1988). We assume the merchantable proportion of wood biomass is constant over the life of a stand, corresponding to what the proportions would be for an individual tree of the typical minimum diameter of trees at harvest (circa 20 cm). The taper equations used to derive these proportions also predict that the proportion of a stem which is merchantable no longer changes

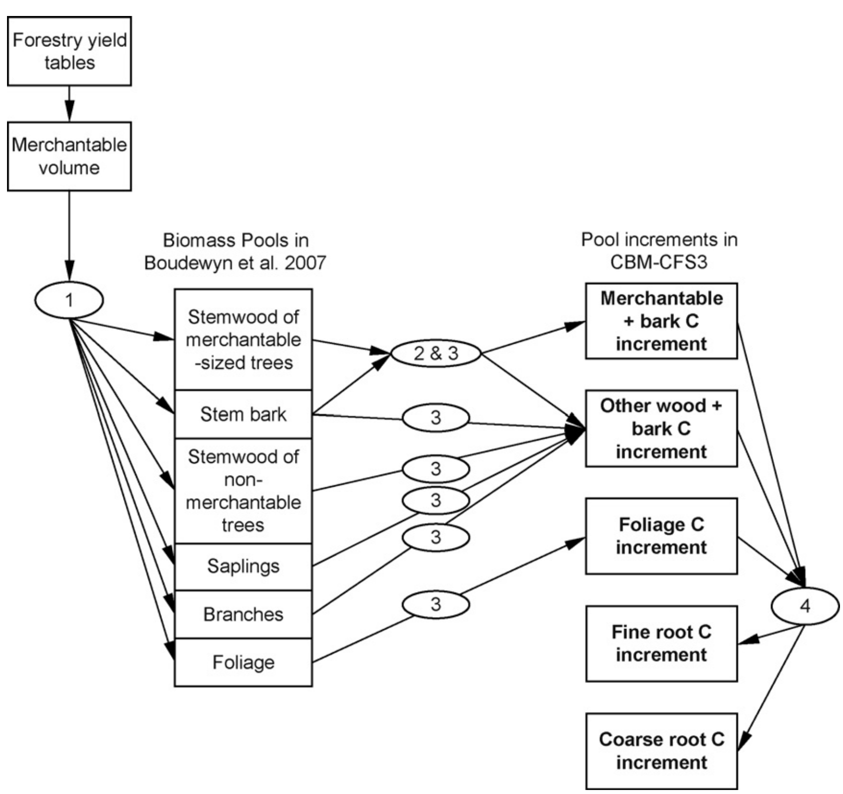

Fig. 4 – Process diagram for CBM-CFS3 conversion of merchantable volume to growth increments. Steps in the conversion are denoted by numbered circles: 1 = stand-level, per ha, volume to live aboveground biomass equations from Boudewyn et al. (2007); 2 = partitioning of stemwood into merchantable and non-merchantable tops and stumps (see Table 3); 3 = conversion from cumulative biomass to units of carbon increment and 4 = stand-level, per ha, aboveground to belowground C equations from Li et al. (2003).

significantly above this diameter. This subdivision primarily impacts C dynamics when harvest is applied. For example, an underestimate of the amount of stemwood biomass that is merchantable could result in excess harvested area, relative to the area that was actually harvested, if the model is provided a carbon-based harvest target (and not area-based targets).

The CBM-CFS3 uses a curve-smoothing algorithm to estimate aboveground biomass when there is little or no merchantable volume. This allows the model to simulate the development of young stands up to the point were trees reach merchantable size. The use of a threshold in the definition of merchantable volume introduces a discontinuity in CBM pools for small-volume stands. The smoothing algorithm reduces this discontinuity, but the merchantable pool will contain sub-merchantable wood at young ages and is therefore not perfectly consistent with a timber supply model's definition of merchantability in young stands. The smoothing-algorithm fits one of several possible non-linear equations to the volume-based values for the total, merchantable, and foliage carbon pools and estimates the other carbon pool as the difference between the total carbon pool and the sum of the merchantable and foliage carbon pools. After checking for internal consistency (e.g. the sum of the component values must be less than the total value), these fitted values are used in the gap between zero merchantable volume at age 0 and the age when the minimum non-zero volume is reached for a given combination of species and ecozone. If the difference between the fitted and volume-based values for total aboveground C is less than a minimum threshold at the age at which the minimum volume is reached, then the model switches from smoothed values to volume-based values. If the difference between the fitted value and the volume-based value are not within this minimum threshold, the search region is first extended by up to 10 years, and the threshold is relaxed until a match point is found.

For each year of a simulation, biomass pool stocks increase in accordance with the growth increment array (see Box 1, Step 7). An example of lodgepole pine growth shows the increasing biomass stocks for the five softwood biomass pools (Fig. 5). The CBM-CFS3 used the splicing algorithm to drive the rapid growth in foliage, other wood, and roots pools from age 0 to 49. At age 50, C transfer to the merchantable pool begins. The total biomass continues to accumulate rapidly until about age 75 when growth slows. The only discontinuity in the slope of the curve is at the year when trees reach merchantable size—when a portion of total stand biomass C is moved from the other wood pool to the merchantable pool.

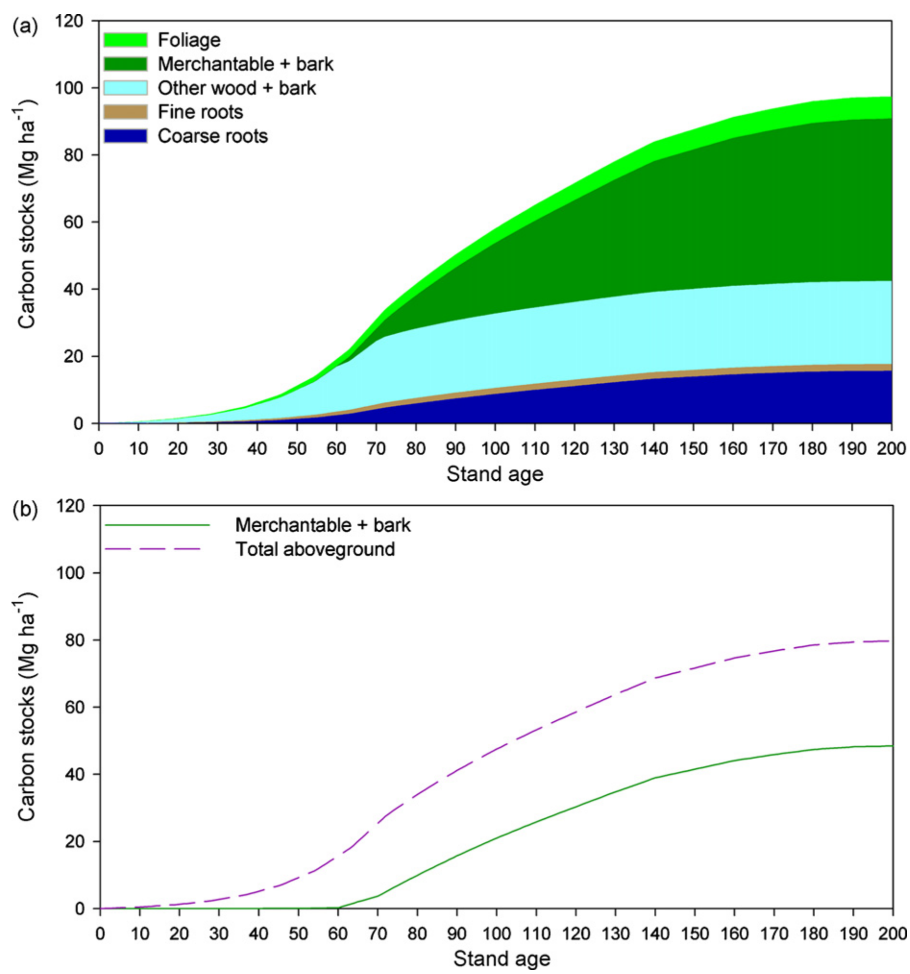

Fig. 5 – (a) Biomass carbon stocks for each pool in an example 1 ha lodgepole pine stand, growing from age zero. (b) A splicing algorithm smoothes the transition from young stands with biomass but no merchantable stems to older stands with merchantable C.

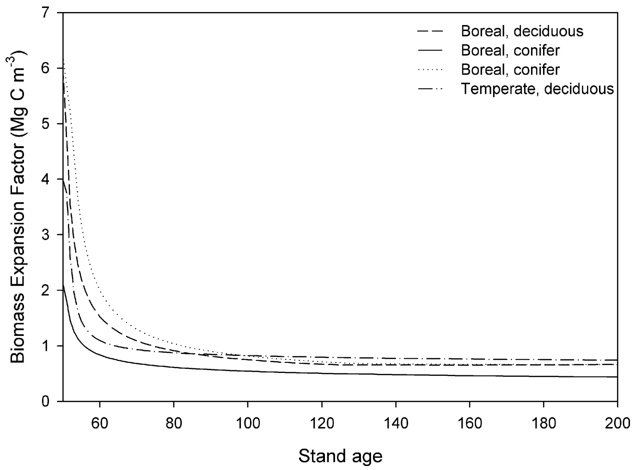

Fig. 6 – Aboveground biomass expansion factors (BEF) for common Canadian forest stand types, as back-calculated from biomass C values estimated by CBM-CFS3 and provided for international reporting. BEF values represent ratios between total stand biomass (Mg) and merchantable stem volume (m^3) based on average growing conditions.

In countries where allometric equations are not available, biomass expansion factors (BEFs) are commonly used in forest C accounting systems (e.g. Tier 2 methodology, IPCC, 2003). Biomass expansion factors are applied to merchantable volume to estimate aboveground or total stand-level tree biomass. These can be back-calculated from the information generated by the CBM-CFS3 to provide a useful point of reference for comparison between models, and for international users making appropriate parameter selections when using the CBM-CFS3 to simulate the C dynamics of forest ecosystems outside of Canada. Fig. 6 provides four example BEFs that we back-calculated from information generated by the CBM-CFS3 for common Canadian forest stand types. As expected, the BEF decreases rapidly as stands develop, and therefore the proportion of biomass in merchantable stemwood increases. In general, these values are lower than those provided for international reporting (IPCC, 2003), reinforcing the value of locally relevant data in reducing the uncertainty of C estimates.

3.3. *Biomass turnover and litterfall transfers*

The CBM-CFS3 uses biomass turnover to represent mortality of biomass and litterfall rates to represent the transfer of the dead biomass to one or more DOM pools. Ecosystem processes represented by these parameters include tree, foliage, branch and root mortality. The model estimates biomass turnover using annual biomass turnover rates (% mortality yr^{-1}) for most stand development up until the point of natural stand break-up where yield curves decline. After this point, turnover from each biomass C pool is added to losses caused by stand break-up. After the CBM-CFS3 estimates biomass turnover, it uses litterfall transfer rates to assign the C to different DOM pools as specified in the model's structure (Table 3). The CBM-CFS3 uses the same biomass turnover and litterfall transfer parameters as CBM-CFS2 (Kurz et al., 1992; Kurz and Apps, 1999) with the exception of fine root turnover that was updated from Li et al. (2003).

Validation of biomass turnover and litterfall parameters is limited by the lack of studies reporting both the amount of turnover and the amount of biomass stock for each component producing the detritus. Both values are required to validate biomass turnover rates. However, we have achieved a degree of validation by comparing model parameters or fluxes against literature values, and estimates derived from readily available datasets.

Literature values of foliage turnover rates for softwood species are 14.4 and 15.2% (Lavigne et al., 2005; Harmon et al., 2004). Analysis of a readily available dataset from the BOREAS research program (Gower and Vogel, 1998; Gower and Vogel, 1999) showed a range of 4–20% across 10 conifer sites. These values are consistent with the CBM-CFS3 calibration of 5–15% turnover, depending on the ecozone. This parameterization was based on senescent needle litterfall reported by Grier (1988) and input requirements for the very fast pools.

Literature values for litterfall rates range from 0.60 to 1.55 $Mg\,C\,ha^{-1}\,yr^{-1}$ for hardwoods (Bray and Gorham, 1964;

Table 3 – Range of biomass turnover and litterfall transfer rates. AG = aboveground, BG = belowground, SW = softwood, HW = hardwood.

CBM-CFS3 pool	Turnover rates[a] (% C yr^{-1})	DOM pool receiving turnover	Litterfall transfer rate (percent of turnover transferred to each DOM pool)
Merchantable stemwood (SW or HW)	0.45–0.67	Snag stems	100
Other wood (SW or HW)	3–4	Snag branches	25
		AG fast	75
Foliage (SW)	5–15	AG very fast	100
Foliage (HW)	95	AG very fast	100
Fine roots (SW or HW)	64.1	AG very fast	50
		BG very fast	50
Coarse roots (SW or HW)	2	AG fast	50
		BG fast	50

[a] Values from Kurz et al. (1992) except for the fine root turnover rate that was updated using parameters in Li et al. (2003).

Table 4 – The parameters used to simulate DOM dynamics in CBM-CFS3. 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 DOM pool (P_t), where $P_{atm} + P_t = 1$. AG = aboveground, BG = belowground, N/A = not applicable.

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

Van Cleve and Noonan, 1975; Lousier and Parkinson, 1976) and 0.20 to 1.10 Mg C ha^{-1} yr^{-1} for softwoods (Weber and Van Cleve, 1984; Fyles et al., 1986; Trofymow and CIDET Working Group, 1998). The lower values are associated with low productivity black spruce and higher values with west coast old-growth Douglas-fir. These values were consistent with estimates from CBM-CFS3: 1.17 ± 0.59 to 1.86 ± 0.58 Mg C ha^{-1} yr^{-1} for hardwoods and from 0.30 ± 0.21 to 0.55 ± 0.21 Mg C ha^{-1} yr^{-1} for softwoods. The CBM-CFS3 model was run for 427 softwood-dominated and 125 hardwood-dominated plots taken from a forest ecosystem C database (Shaw et al., 2005) and from the Ontario Terrestrial Assessment Program (Ecological Land Classification Group, 2005). Softwood plots covered a range of species from across Canada while hardwood plots were dominated by trembling aspen (*Populus tremuloides* Michx.).

Other wood biomass turnover is parameterized at 3–4 mass% yr^{-1} (Kurz et al., 1992). The other wood pools include wood from highly diverse biomass components including branches, living stumps, tree tops and non-merchantable trees. It is difficult to validate the parameterization against field measurements of mortality and litterfall collection because it is unlikely that turnover for all of these components would be measured at one site. However, an examination of the literature for estimates for components of the other pool provides some support for the other pool turnover parameterization. For example, recent studies estimated turnover of branch-wood in Canada ranged from <1 to 20% (Lavigne et al., 2005; Bernier et al., 2007). Also, turnover rates for non-merchantable stemwood were estimated using a sophisticated stand-level model developed by the British Columbia Ministry of Forests, the Tree and Stand Simulator (TASS v2.07) (di Lucca, 1999). One hundred and twenty-six mortality tables were generated for eight species and five or six site index classes. These simulations covered most of the merchantable stand conditions in British Columbia. Each mortality table included stands aged 10–200. The annual turnover rate for non-merchantable stemwood ranged from 0 to 5.8 volume% yr^{-1}. Thus, the branch-wood turnover rates and results from the TASS model are consistent with the parameterization used in the CBM-CFS3 for turnover of the other wood pool.

3.4. *Decay dynamics*

Decomposition for every DOM pool is modelled 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). Slow DOM pools release all of their decayed material to the atmosphere. Decay dynamics are simulated in each annual time step (see Box 1, Step 7).

Applied decay rates (a_k) are calculated for each DOM pool (k) as

$$a_k = \mathrm{BDR}_k \times \mathrm{TempMod} \times \mathrm{StandMod} \tag{1}$$

where a_k is the applied decay rate (yr^{-1}), BDR_k is the base decay rate (yr^{-1}) at a reference mean annual temperature of 10 °C, TempMod is a temperature modifier and StandMod is a stand 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:

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

where MAT is the mean annual temperature of each spatial analysis unit i (MAT_i), RefTemp is the reference mean annual temperature of 10 °C, and Q_{10} is a temperature coefficient (Table 4).

The stand modifier (StandMod) simulates enhanced decomposition that can occur under an open canopy and is calculated as

$$\mathrm{StandMod} = 1 + (\mathrm{MaxDecayMult} - 1)\, e^{(-b \times \mathrm{TotBio}/\mathrm{MaxBio})} \tag{3}$$

where MaxDecayMult is the open canopy decay rate multiplier, TotBio is the total aboveground biomass, MaxBio is the maximum aboveground biomass for the specified stand type, and b = 6.93 (Kurz and Apps, 1999). In CBM-CFS2 the default value for MaxDecayMult was two. In the CBM-CFS3 the value defaults to one because more recent studies that examined open canopy effects on decomposition indicated that decomposition rates are not always higher under open canopies and that decomposition rate responses may be ecosystem specific (Yanai et al., 2000). Although the default value is one, users can, if appropriate, change the MaxDecayMult value in the CBM-CFS3 interface to simulate enhanced or reduced decomposition when the overstory is removed (e.g. Prescott et al., 2000).

The BDR, Q_{10} and P_t for the medium, above and belowground fast and belowground very fast pools in the CBM-CFS3 are the same as in CBM-CFS2 (Kurz and Apps, 1999) (Table 4).

We updated the BDR, Q_{10} and P_t for the aboveground very fast pool in the CBM-CFS3 based on recent calibration work (Smyth et al., in review) using long-term data from a national litterbag decomposition experiment (Trofymow and CIDET Working Group, 1998). The calibration of base decay rates for the slow pools used an iterative process to minimize the mean bias (Smith et al., 1997) between modelled estimates and measured values for stand-level data. The data used were measurements of forest floor and mineral soil C, including percent carbon or percent organic matter by horizon, horizon thickness, and soil profile classification from a forest ecosystem C database (Shaw et al., 2005) and from the Ontario Terrestrial Assessment Program (Ecological Land Classification Group, 2005). The model assumes the Q_{10} for the aboveground slow pool is the same as for the aboveground very fast pool. Since the base decay rates calibrated for individual plots exhibited no discernable trend with MAT we set the Q_{10} for the belowground slow pool equal to one.

For the new snag stem and snag branch pools, we set the base decay rates to half the rate of dead fallen logs (medium pool) and fallen branches (aboveground fast pool), respectively. This was based on evidence from comparative studies indicating that decay rates for snags are lower than for CWD in contact with the forest floor (Krankina and Harmon, 1995; Wei et al., 1997; Storaunet and Rolstad, 2002).

The processes modelled using physical transfer rates include the fall of snag stems and snag branches to the medium and fast DOM pools, respectively, and the translocation of dissolved organic matter from the above- to belowground slow pool. We set the snag stems annual transfer rate to 3.2% based on half-life estimates for softwood snag boles fragmentation (Harmon et al., 1986). This parameter value is within the range of reported values for temperate and boreal systems (2.17–8.4%) (e.g. Huggard, 1999; Runkle, 2000). We set the physical transfer rate from snag branches to the aboveground fast DOM pool at 10% based on qualitative descriptions of decay classes (e.g. Raphael and Morrison, 1987). The physical transfer rate from the above- to belowground slow pool of $0.006\,yr^{-1}$ is based on the transfer rate for dissolved organic C reported in the literature for some Canadian forest soils (Moore, 2003). This parameter value was estimated using the assumptions of a mean forest floor C content of $35\,t\,ha^{-1}$ and mean flux of $22\,g\,m^{-2}\,yr^{-1}$ (Moore, 2003).

3.5. *Simulation initialization*

The CBM-CFS3 uses a simulation initialization procedure that links biomass, DOM dynamics and historical disturbance regimes (Kurz and Apps, 1999) to minimize artifacts appearing as changes in soil pools at the beginning of a model run (e.g. Peltoniemi et al., 2006). The model's approach to simulation initialization is different from those that use observed C stocks to initialize the model or calibrate slower pools to match observed C stocks in the absence of disturbance (e.g. Liski et al., 2005). The underlying assumption of these models is that the observed C stocks represent equilibrium stocks. However, observed soils may not be in equilibrium due to disturbances and very long turnover times of stable compounds (Wutzler and Reichstein, 2007). The CBM-CFS3 approach yields non-equilibrium soil conditions that reflect changes in disturbance regime, management or species at the start of the simulation, relative to historical conditions.

The simulation initialization populates the biomass and DOM C stocks for each stand (see Box 1, Steps 4 and 5). The default assumption for initialization of the model's DOM pools is that the historic natural disturbance regime is stand-replacing fire. Disturbance-return intervals used for initialization differ for each terrestrial ecozone and vary between 75 years in Prairie ecozones to 300 years in the Pacific Maritime ecozone. We derived the interval parameterization from average ages in forest inventory data and literature from eastern (Blais, 1983; Bergeron et al., 2004) and western (Johnson, 1992; Parminter, 1995) Canada. The user can modify these default values. The model starts the initialization process with all pools containing zero carbon stocks. The model simulates each stand through repeated iterations of growth followed by stand-replacing disturbance, gradually increasing the stock size in the DOM pools. The cycles continue until the sum of the above- and belowground slow DOM C pools at the end of two successive rotations meets a difference tolerance of 1.00% (Fig. 7). The CBM-CFS3 typically reaches the tolerance limits between 10 and 30 iterations. The definition of quasi-equilibrium used in the CBM-CFS3 is based on a comparison of differences between rotations, not individual time steps as is used elsewhere (e.g. Smith et al., 2005).

Once the quasi-steady state has been reached, the model simulates one more rotation terminated by the last known stand-replacing disturbance, or, if that is unknown, one more default (fire) stand-replacing disturbance. At that time a transition from a historical yield table to a current yield table is also possible. The model then grows each stand to its current age as defined in the inventory. This methodology ensures continuity between simulation initialization and the simulated DOM dynamics. If the disturbance and management activities have changed the population dynamics of the forests, either prior to or during the simulation, then changes in the slow DOM pools will result that are consistent with our current ecological understanding.

4. Representation of disturbances

The CBM-CFS3 simulates natural and anthropogenic annual disturbances because these have been shown to significantly influence forest C dynamics (e.g. Kurz and Apps, 1999; Kurz et al., 2008a, 2008b). In addition, the GPG encourages explicit reporting of natural disturbances, forest management activities and land-use change (IPCC, 2003). Disturbances are driven

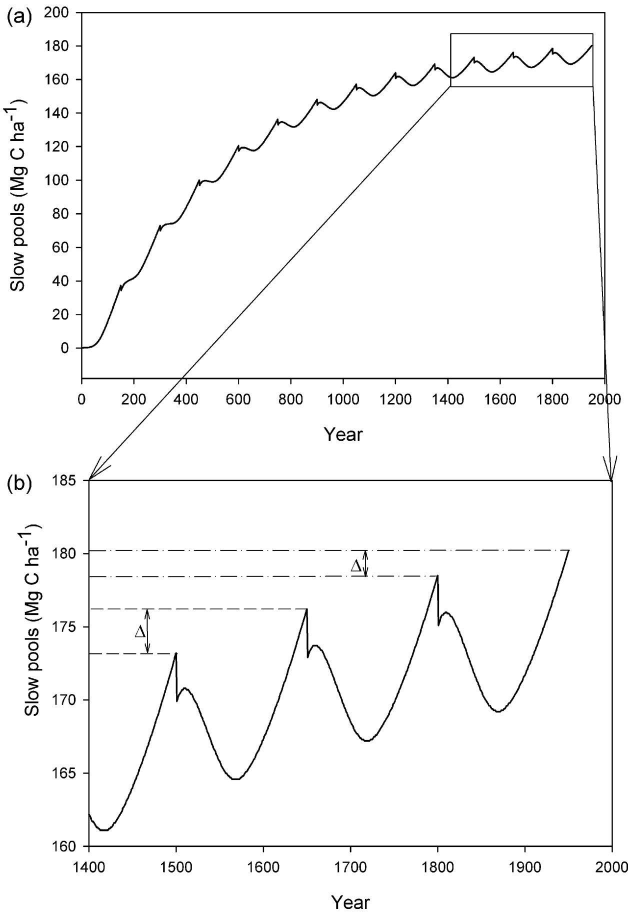

Fig. 7 – Soil carbon stocks during the simulation initialization procedure for a hypothetical lodgepole pine stand with a 150-year historical fire return interval, where the lower panel is a subset showing the last four cycles. The initialization is considered complete when the difference (*Δ*) between iterations stabilizes to ≤1.0%.

by available activity data such as forest health aerial surveys, harvested volume statistics or fire monitoring as provided by the user. There are four elements to disturbances in the model: controls, impacts, post-disturbance dynamics and land-use change accounting. Disturbance controls determine how the model selects stand types to be disturbed. Disturbance impacts are parameters that determine the transfer of C between pools or out of the ecosystem. Post-disturbance dynamics variables control the regeneration of the affected stand(s). Land-use change accounting affects the disturbance impacts, post-disturbance dynamics and the calculation of C stocks and fluxes when deforestation or afforestation occurs. All of these elements can vary temporally and spatially between individual or groups of spatial units (see Box 1, Step 6).

4.1. *Disturbance controls*

The CBM-CFS3 provides flexible disturbance control options to accommodate diverse activity data describing a wide variety of disturbance types. Control options include spatial criteria, stand characteristics, sorting of inventory, and targets. The spatial location of a disturbance event may be limited to a single spatial unit or a disturbance group—a collection of spatial units. The CBM-CFS3 can also use non-spatial stand characteristics defined in the inventory (e.g. species, age, amount of C in individual pools, and stand history) to select a list of stands eligible to be disturbed. For example, a salvage logging disturbance type can be set up with criteria that the stand was disturbed by fire within the previous five years. Likewise, multi-year insect outbreaks can be simulated with more severe impacts occurring only on stands with lighter infestations by the same insect in previous years. Once the list of eligible stands is established, the CBM-CFS3 sorts the stands. There are 13 sorting algorithms, for example, random or highest amount of merchantable stemwood (Kull et al., 2006). Once sorted, the CBM-CFS3 then applies the disturbance target to the first stand in the list.

Annual targets of the extent of forests affected by a disturbance event can be specified in three ways: as an area, as the amount of merchantable C, or as a proportion of all eligible stands. CBM-CFS3 applies the disturbance by stepping through all eligible stands and simulating the disturbance impacts until either (1) the target is achieved or (2) all stands in the eligibility list have been affected. Stands may be completely or partially affected by the disturbance. An efficiency variable controls the maximum proportion of a stand area affected, for example, to represent wetland buffers in harvest systems. This allows some control over the number of stands that will be disturbed in a given year. Note that the merchantable C target is applied to the pool that includes stemwood and bark. Therefore, harvest statistics (usually defined as volume without bark) must be increased to allow for the contribution of bark to achieving the target. The amount of area and C affected by a disturbance per time step are reported in the model output.

4.2. *Disturbance impacts*

In the CBM-CFS3, disturbance impacts are defined using a matrix that describes the proportion of C transferred between pools, as fluxes to the atmosphere, and as transfers to the forest products sector (Fig. 3) (for an example, see Table 5 in Kurz et al., 1992). The proportions are specific to each disturbance type and can vary spatially, to reflect spatial differences in disturbance intensity, e.g. fire (de Groot et al., 2007). The model includes a suite of default disturbance matrices or users can define their own using the graphical user interface.

Disturbance matrices provide an efficient means to affect the large number of pools and fluxes of C, including the pools described in Table 2 plus losses from the ecosystem (CO_2, CH_4, CO to the atmosphere and to the forest products sector). This flexibility allows for realistic modelling of management activities and natural disturbances. One of the key improvements in the disturbance modelling – of CBM-CFS3 compared to CBM-CFS2 – is the capability of simulating partial mortality of the stand. For example, an infestation by a conifer-foliage-eating insect may kill 40% of the softwood trees in a stand, consume 80% of the softwood foliage, and release 5% of the C to the atmosphere through respiration. In such a case, the insect affects softwood components but hardwoods pools remain unaffected.

There are 234 default disturbance matrices provided with the CBM-CFS3 (Kull et al., 2006); the parameters for all of these can be viewed using the model's Disturbance Matrix Editor interface. Custom matrices can be made by model users. Here we describe recent calibration work on the impacts of mountain pine beetle (*Dendroctonus ponderosae* Hopk.), spruce budworm (*Choristoneura fumiferana* Clem.), harvest, and fires in Canadian forests. An unprecedented outbreak of mountain pine beetle led to quantification of beetle-caused mortality at the landscape scale (Kurz et al., 2008a). Mountain pine beetle impacts were simulated as partial-mortality events, which killed a portion of softwood (host) biomass pools. The beetle impacts were parameterized by translating the damage classes reported in the aerial overview survey into percent of crown killed and then into percent of softwood biomass killed for use in the CBM-CFS3. We validated our beetle impact calibration against estimates of volume killed produced by the British Columbia Ministry of Forests and Range (Kurz et al., 2008a).

Impacts for spruce budworm, a defoliator, were calibrated based on data from the previous outbreak on the assumption that any future outbreaks will be of similar magnitude, and that management responses (e.g. spray programs) will also be similar. We used information on past population dynamics and defoliation in the Spruce Budworm Decision Support System (Maclean et al., 2001) to construct a set of impact instructions that apply to 95% of the host forest within an outbreak area. These instructions prescribe annual levels of growth reduction and mortality in affected stands in the CBM-CFS3 (Dymond et al., in preparation).

Forest management activities parameterized in the CBM-CFS3 as disturbance matrices include clearcut logging with or without slash burning, partial cutting, commercial thinning (25–75% removal in 5% increments), and salvage logging following fire or insect disturbances. Calibration of the disturbance matrices involved extensive interviews with provincial and territorial forest management agencies from 2001 to 2004 through the National Forest Sinks Committee of the Canadian Council of Forest Ministers. We validated the harvest impacts by reviewing the results of model simulations with the original contributors and by comparing model simulation results with nationally available statistics for area and volume harvested (NFDP, 2007). The harvested stemwood leaves the ecosystem, so model output reports it as a flux to the forest products sector. In accordance with the IPCC guidelines, we currently report these removals as instantaneous emission to the atmosphere for UNFCCC reporting purposes (IPCC, 2003).

We calibrated the forest fire disturbance matrices using a national forest inventory, fire weather information, and the Boreal Fire Effects model (BORFIRE; de Groot, 2006). BORFIRE models the amount of fuel consumed (and emitted to the atmosphere) in response to weather-induced burning conditions and the type of fuel being burned. The Canadian Wildland Fire Information System (de Groot et al., 2007) calculated the fire weather conditions (Van Wagner, 1987) for the period 1990–2005 and assigned them to fires using spatial and temporal matching. We estimated the 1990 pre-fire forest condition from our national forest C inventory (Kurz and Apps, 2006; Environment Canada, 2007). The fuel consumption results from BORFIRE were then compiled into an average disturbance matrix, specific to each ecozone, for application in the CBM-CFS3. The proportion of each pool that is consumed by the fire differs because each pool represents a different potential source of fuel available to the fire and because the weather was different during each fire (Table 5). For some pools, such as softwood merchantable, no C is consumed and emitted to the atmosphere in the CBM-CFS3. For others, such as aboveground slow, the proportion consumed ranges from 0.038 to 0.522, depending on the ecozone. The emissions from wildfires and biomass burning in any particular simulation will depend on both the disturbance matrix and the forest inventory used. Of the C emitted during wildfire, 90% is reported as CO_2, 9% as CO and 1% as CH_4 based on empirical data from the literature (Cofer et al., 1998; Kasischke and Bruhwiler, 2003).

Table 5 – Range of variation in ecozone-specific parameters describing the proportion of C consumed and emitted as gas (primarily CO_2) to the atmosphere from each C pool type during wildfires. AG = aboveground, BG = belowground, SW = softwood, HW = hardwood.

Source pools	Min	Max
Merchantable (SW)	0.0	0.0
Foliage (SW)	1.0	1.0
Other wood (SW)	0.25	0.25
Coarse roots (SW)	0.0	0.0
Fine roots (SW)	0.019	0.261
Merchantable (HW)	0.0	0.0
Foliage (HW)	0.995	1.0
Other wood (HW)	0.0	0.034
Coarse roots (HW)	0.0	0.0
Fine roots (HW)	0.044	0.464
AG very fast DOM	0.904	1.0
AG fast DOM	0.642	0.936
Medium DOM	0.319	0.851
AG slow DOM	0.038	0.522
BG very fast DOM	0.0	0.0
BG fast DOM	0.0	0.0
BG slow DOM	0.0	0.0
Snag stems (SW)	0.0	0.0
Snag branches (SW)	0.0	0.0
Snag stems (HW)	0.0	0.0
Snag branches (HW)	0.0	0.0

In addition to, or instead of transferring C between pools, disturbances in the CBM-CFS3 can also affect the growth of a stand. To simulate a reduction in growth in the year of a disturbance, the model multiplies the growth increment by a proportion (<1.0). Currently, we have implemented growth reductions such as those caused by insects. Future versions will allow disturbances, such as fertilizer application, to increase the growth rate.

An example illustrates the model behaviour in two possible scenarios developed for simulating bark beetle impacts (Fig. 8). A five-year bark beetle infestation was simulated as a series of partial mortality events hitting a 1-ha stand of 100-yr-old lodgepole pine. The outbreak started in year 3 with 5% mortality, mortality rates for the next four years were 10, 10, 30, and 50%. In a second simulation, the first three years of

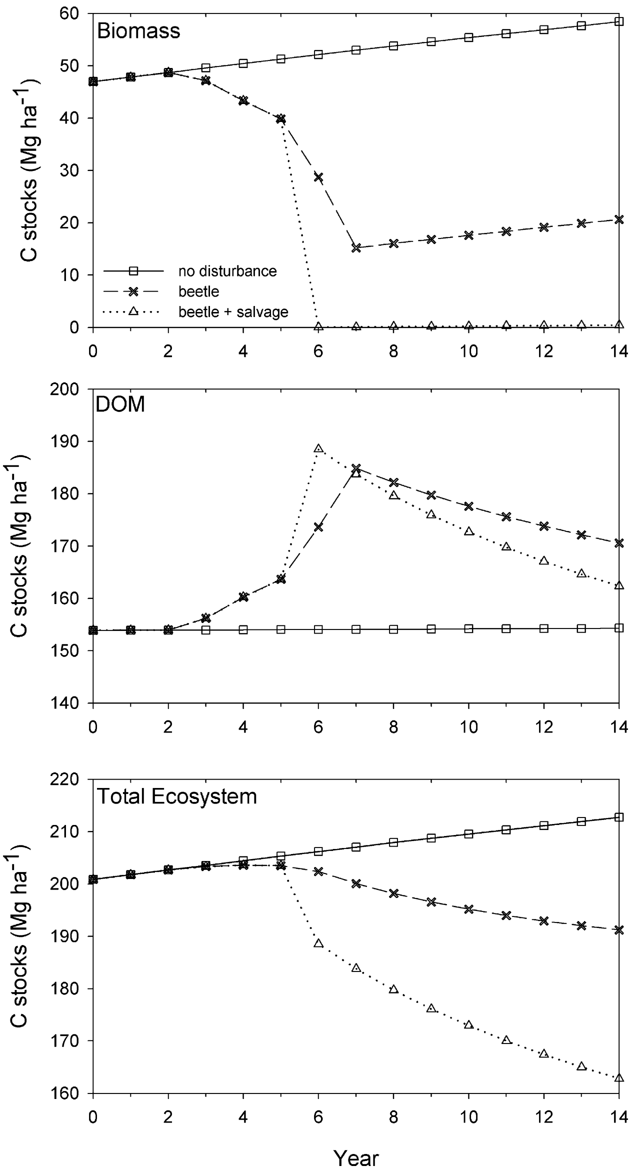

Fig. 8 – Example simulation of a lodgepole pine stand affected by no disturbance, beetle-caused partial mortality in years 3 through 7, or beetle-caused partial mortality in years 3 through 5 followed by a salvage logging operation in year 6.

bark beetle impacts were followed by a clearcut logging event with 85% of the live merchantable stemwood and 50% of the snags going to the forest products sector. The bark beetle and logging cause transfers of biomass to the DOM pools where it decays. The logging also causes transfers to the forest products sector resulting in a sharp drop in ecosystem C stocks in year 6. The total ecosystem C stocks are initially decreasing following these disturbances because carbon uptake through growth is exceeded by carbon losses from decomposition.

4.3. *Post-disturbance dynamics*

To simulate stand succession rules and various management practices, the CBM-CFS3 framework includes flexible options to represent post-disturbance biomass dynamics. The biomass dynamics are influenced by the disturbance being either stand-replacing (age reset to zero) or causing partial mortality (age unchanged). In a stand-replacing disturbance, all merchantable trees are killed. The CBM-CFS3 sets the age to zero and assumes the stand starts re-growing on the same growth trajectory, unless given other instructions by the user. Transition rules provide the opportunity to simulate regeneration delays, planting or changes in species. Following a partial mortality event, the age of the stand and corresponding growth increments remain unchanged. This is an approximation that we could improve on with more field data quantifying post-disturbance growth response. Users can alter this assumption by defining transition rules.

Transition rules provide flexibility for representing the post-disturbance dynamics of a forest stand. They specify the type of forest that would occupy the land area following a disturbance. The CBM-CFS3 represents the transition rules in a deterministic way—by associating a disturbance type and a stand type (i.e. a combination of classifiers) with one or more post-disturbance types of stands. The model allows the user to specify the classifier values that define the stand type resulting from the disturbance (and therefore a new growth array), a regeneration delay value (the numbers of years for the regeneration delay of the new stand), and the age from which the new stand will begin growing. The CBM-CFS3 is now able to recognize four new stand types per source stand type following disturbance (the CBM-CFS2 only allowed two). Any remaining proportion of disturbed area not handled by these transition rules will retain the original stand type.

To illustrate the use of transition rules, three different post-disturbance dynamics were simulated following a clearcut of an 85-year-old lodgepole pine stand (Fig. 9). In the normal scenario, the default transition rule returned the stand to age zero and it immediately began growing using the same growth increment array. In the planting scenario, the regrowth was accelerated by 20 years and in the delayed scenario the appear-

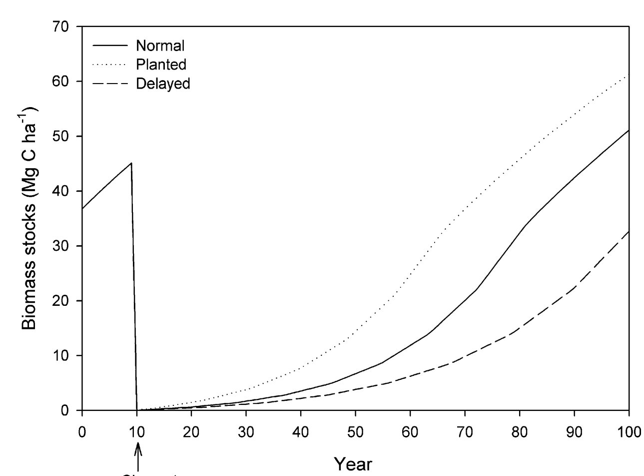

Fig. 9 – Three model scenarios of a hypothetical lodgepole pine stand following clearcutting in year 10. Depending on the transition rule, the biomass stock accumulation may be delayed, regenerate normally, or be accelerated due to planting. Example for illustration of model behaviour only.

ance of merchantable volume in the yield table was postponed by 20 years, slowing regrowth. We designed these extreme examples only to illustrate the model behaviour.

The post-disturbance DOM dynamics in the CBM-CFS3 reflect changes to stocks resulting from the disturbance and follow patterns determined by the parameters described in the DOM dynamics Section 3.4. The impacts of different types of disturbances on C inputs to the DOM pools influence DOM C stocks and fluxes for decades after the disturbance events. We illustrate the impact of different disturbance types on the dynamics of total DOM C and individual DOM pools by comparing a wildfire and a traditional clearcut disturbance (Fig. 10). The dynamics of each group of DOM pools are significantly different in response to the two disturbance types (Fig. 10a–e). However, 60 years after a stand-replacing fire or clearcut disturbance the total DOM C stocks converge on a value of about 80 Mg C ha^{-1} (Fig. 10f). The very fast C stocks decrease rapidly (Fig. 10a) at the time of disturbance because inputs from foliage and roots are halted once the trees are removed, and slowly recover as the new stand grows. The reduction is greater post-fire because most of the existing aboveground very fast pool (L horizon) is consumed in the fire. Post-fire, significant C stocks remain in the snag pool (Fig. 10e) which gradually decays and transfers to the medium and then slow pools (CWD and soil, respectively) (Fig. 10c and d). In contrast, no C is transferred to the snag pool post-harvest because merchantable stemwood transfers to the forest products sector (Fig. 10e) and the medium pool increases slightly because of contributions from harvest residues (Fig. 10c). In this traditional clearcut and salvage simulation, snags are felled but alternative policies, such as leaving wildlife trees, can be simulated. The slow and medium C stocks increase following the clearcut as C from the other DOM pools is transferred to the slower pools (Fig. 10c and d). Conversely, medium and slow C stocks are sharply reduced at the time of a fire because a portion of the stock burns. The slow C pools gradually recover as they receive C from the other DOM pools. Thus, in this example, after 60 years the remaining difference between post-fire and post-harvest total DOM C stocks of about 10 Mg C ha^{-1} can largely be attributed to combustion of CWD (medium pool) that occurred at the time of the stand-replacing fire.

4.4. *Land-use change accounting*

Changes in land use are handled as disturbances in CBM-CFS3, but they have some unique characteristics. We added land-use change accounting to CBM-CFS3 because, globally, land-use change accounts for 20% of anthropogenic emissions of GHGs (Denman et al., 2007). The effects of land-use change can be both positive and negative. The clearing of forests to make way for another land-use such as agriculture or settlements – referred to as deforestation – results in increased emissions to the atmosphere (IPCC, 2003). The creation of new forests, through tree-planting on non-forested lands, referred to as afforestation or reforestation, can sequester additional C from the atmosphere. To account for the contribution of land-use change to the global C balance, the UNFCCC and Kyoto Protocol distinguish emissions and removals of GHGs on lands that have been subject to a continuous (>20 years) land-use, such as forestry or agriculture, from those that occur on lands that have recently undergone a change in land use, e.g. a conversion of forests to non-forest land-use, or vice versa.

The CBM-CFS3 modelling framework has been designed to simulate the impacts of land-use change, such as changes in land-areas and C stocks, and to facilitate accounting of land-use change impacts following the requirements of the UNFCCC and Kyoto Protocol and the appropriate guidelines of the IPCC (IPCC, 2003, 2006). Afforestation and deforestation are represented as disturbance types with their own disturbance matrices and transition rules. The ecosystem C dynamics following land-use change disturbances are simulated using the same algorithms described elsewhere in this paper, although following deforestation, the model assumes no biomass accumulates on deforested lands. Unlike other disturbances simulated in the model, deforestation and afforestation trigger a change in the land-use class. Deforestation involves the conversion of forest to a non-forested land-use class (cropland, grassland, wetland, settlements or other), whereas afforestation involves the opposite conversion (from non-forest to forest). This change in land-use class occurs before any disturbance impacts are calculated, such that all disturbance impacts from afforestation or deforestation are reported in the new land-use class (see Box 1, Step 6) as required by the IPCC guidelines. The CBM-CFS3 assumes that all simulations involving land-use change begin in 1990 and reports areas in various classes accordingly.

One additional difference between afforestation and other disturbances simulated in the model is the initialization of slow soil pools of non-forest stands prior to afforestation. The CBM-CFS3 is not designed to simulate growth of non-woody species or agricultural practices, consequently the simulation initialization routine described in Section 3.5 cannot be used to initialize the slow soil pools for non-forested stands. Instead, the default initial values for slow C stocks on non-forest land are based on literature values ranging from 40 to 114 Mg C ha^{-1}, depending on soil type (Janzen et al., 1997). Additionally, for most simulations involving afforestation, we assume that the biomass and other DOM pools are empty. For example, agricultural fields converted from an annual crop to forest would not have any standing dead trees or forest floor. These C pools are considered empty prior to plantation establishment. Users can provide initial C stocks to better represent specific afforestation projects, where such data are available.

The impacts of clearing land for deforestation are represented using matrices that are similar to those used for harvesting, since this is often the dominant method of land clearing. Unlike harvesting, however, deforested lands do not regenerate to forest. Deforestation clearing practices can be generalized as four groups: clearcutting, clearcutting and burning of residuals, clearcutting and stump-pulling, or flooding during reservoir creation. To simulate deforestation initiated by clearcutting, merchantable stemwood is removed from the ecosystem, accounted for as a transfer to forest products, and any remaining materials are left to decay on site. When the residuals are burned, the proportions of the pools that are consumed are derived from the fire disturbance matrices provided for each province/territory-ecozone combination. Stump-pulling, piling of woody debris, soil mixing and scarification of sites requires unusual transfers in the disturbance matrices. Specifically, the belowground fast pool is

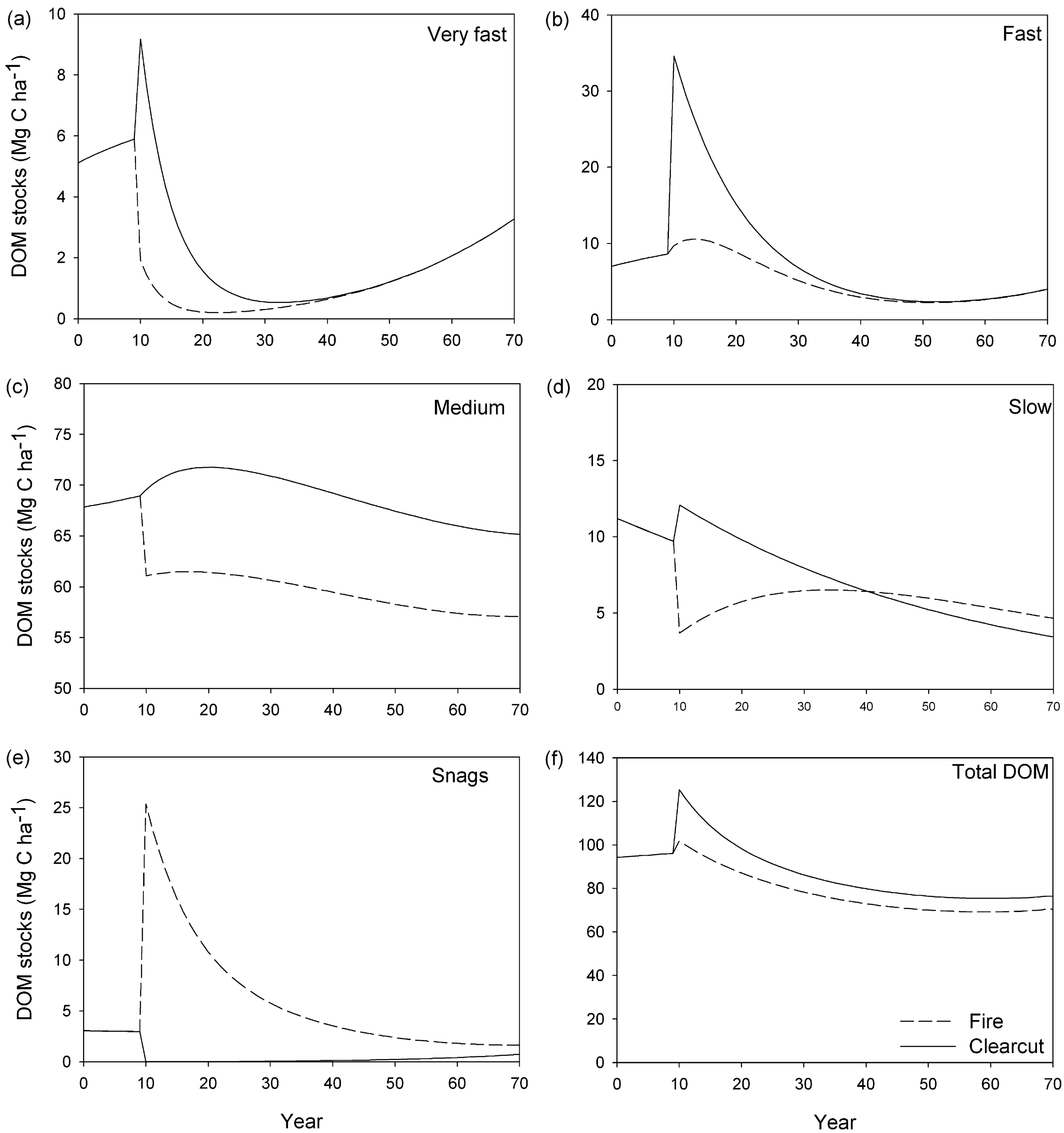

Fig. 10 – Disturbance type affects the size and composition of DOM pools, as shown in these simulations for a hypothetical lodgepole pine stand during regrowth following either a stand-replacing fire or a traditional clearcut harvest in year 10. Note that each panel uses a different y-axis scale.

transferred to aboveground fast pool whereas aboveground very fast and aboveground slow are added to their belowground equivalents. The disturbance matrix for flooding kills all biomass and transfers this to the corresponding DOM pools, but otherwise leaves the DOM pools intact.

Fig. 11 shows the net effect of land-use change accounting rules, disturbance matrices and non-forest stand initialization. At the start of the simulation there were three stands: two forested and one cropland. In year 10, one forest stand was deforested and converted to agricultural use. It remained in the "Forest Converted to Cropland" land-use class for 20 years before changing to "Cropland". For comparison purposes, the second forest stand experienced no disturbances during the simulation. A stand that started as "Cropland" was included in the simulation inventory for the first 20 years, but we did not consider the C dynamics until the afforestation event occurred. At that point, the land-use class changed to "Cropland Converted to Forest" until year 40, after which the stand became part of the permanent forest (Forest remaining Forest).

Fig. 11b illustrates an accounting artifact. Simply put, C stock changes do not reflect emissions and removals (sequestration) of gaseous C when land is moving between classes. The sharp drop in forest C stocks in year 10 and the sharp increase in year 40 are the result of changes in the categoriza-

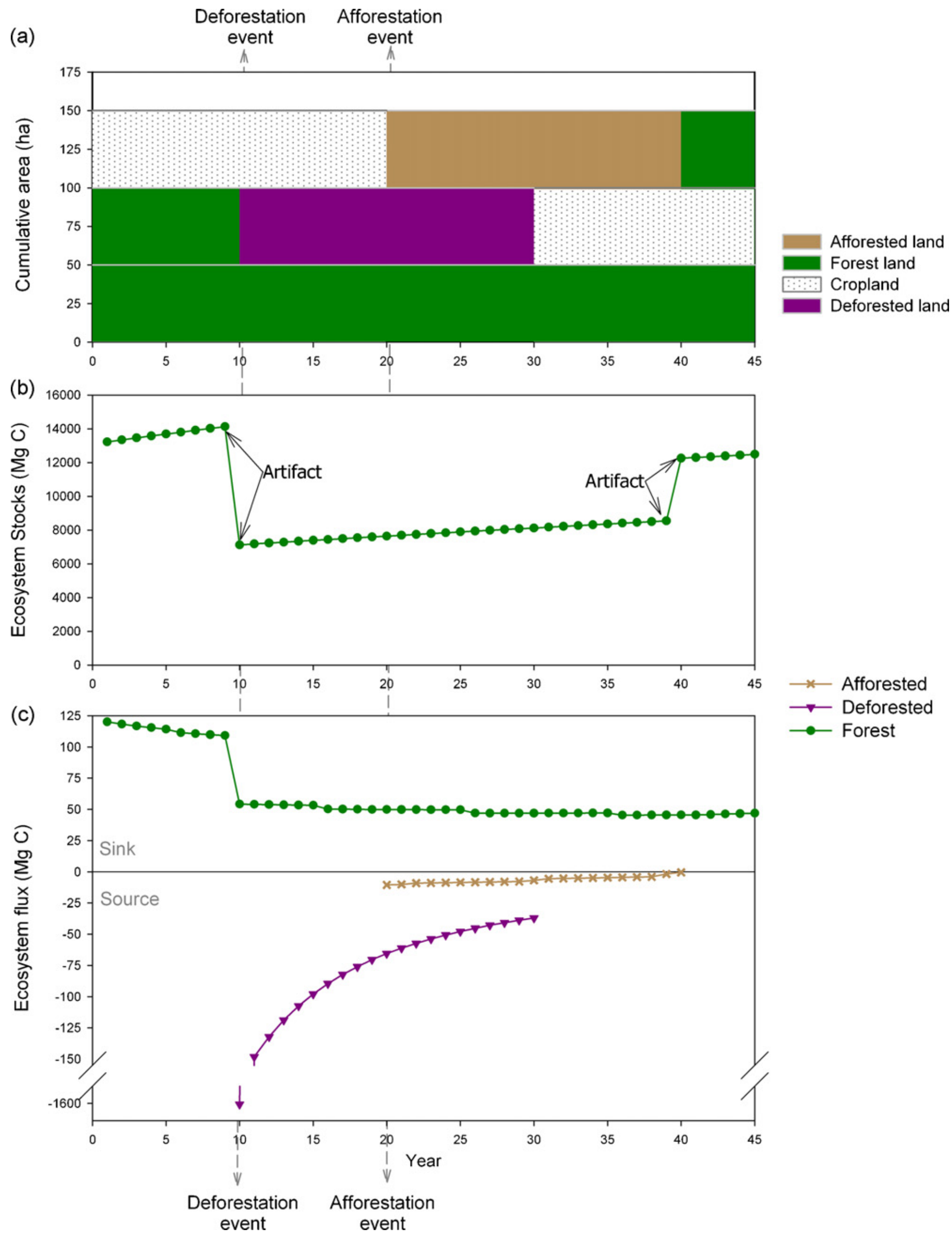

Fig. 11 – Examples of area and C flux accounting in the CBM-CFS3 under land-use change scenarios. (a) Land-use class changes over time for three 50 ha stands. Deforestation and afforestation events triggered the land class changes in year 10 and 20. After 20 yrs, the land conversion is considered complete and the land-use class changes again to a permanent state. (b) Carbon stocks reflect the movement of carbon between different land classes. The sharp drop in forest carbon stocks in year 10 and the sharp increase in year 40 are the result of changes in land classes, not true emissions or sequestration by the forest. (c) Fluxes reflect the emissions and gains by each land-use class.

tion of land into land-use classes on the 150 ha landscape, not true emissions or removals by the forest ecosystem. Panel (c) shows the losses and gains by each of the land-use classes. Under the reporting requirements of the UNFCCC, the annual C fluxes (Panel c) for each land-use category are reported.

The current model is not designed to estimate post-disturbance C stock changes in deforested areas that have been converted to agricultural use (where there are additional factors such as crop biomass, manure input or ploughing), shrubland, or areas that were flooded during reservoir creation (where the mechanisms for decay differ because C is submerged).

5. Model outputs and indicators

The CBM-CFS3 provides a number of outputs that can be used to evaluate C stocks and stock changes, GHG emissions and to evaluate other forest indicators of interest for reporting or model validation purposes. At the end of each year the model reports C stocks and fluxes. The CBM-CFS3 reports the annual C transfers between pools, emissions to the atmosphere, and transfers to the forest products sector for each pool, summarized by classifier set and land-use class (see Box 1, Step 9). Transfers and emissions associated with different disturbance types are reported separately so that the direct impacts of different disturbance types can be evaluated. Indirect impacts, however, cannot all be reported separately in the model output. For example, the direct emissions of C into the atmosphere and the transfers of C from living to DOM pools as a result of fire are reported by the model, but the subsequent release of C from decay of fire-killed biomass is not reported separately from the release of C from decay of other DOM and soil pools on site.

We frequently use the CBM-CFS3 outputs reporting the annual stock change for a pool and for the total ecosystem (see Box 2). The annual stock change for a biomass pool is effectively the net growth increment minus the losses. The annual stock change for a given DOM pool is the increase due to transfers into the pool (due to biomass turnover, decay dynamics or disturbances) minus the losses due to decay dynamics or disturbances. The sum of the stock change of all pools is the total ecosystem stock change. It indicates the annual net ecosystem C flux. Because this is a forest-based model, the sign convention on the output is negative for losses from the ecosystem and positive for accumulation within the ecosystem. The CBM-CFS3 reports GHG fluxes between the atmosphere and the forest lands, as well as those associated with land-use changes. The GHG estimate is reported as carbon dioxide equivalents (CO_2e). It includes emissions and removals of CO_2, and additional emissions of CH_4, N_2O, and CO due to wildfires multiplied by their global warming potential as appropriate for reporting under the Kyoto Protocol (IPCC, 1997). For all disturbances that involve burning, 90% of the C losses from burned organic matter goes into CO_2 emissions, the remainder being emitted as CH_4 (1%) and CO (9%). The

Box 2: General equations for stock change

The stock change for a given biomass pool (i) is:

$$\Delta BIO_i = g_i m_i - d_i BIO_i - b_i BIO_i + b_i BIO_i$$

where

BIO_i is the total C stock of the ith pool,
g_i is the net growth increment,
m_i is the growth increment modifier,
d_i is the proportion of the ith pool that is lost due to disturbance,
b_i is the rate of biomass turnover of the ith pool that is transferred to DOM,
$+b_i BIO_i$ is the regrowth of biomass turnover.

Mathematically, $-b_i BIO_i$ and $+b_i BIO_i$ cancel each other out. They are provided here to help explain the approach.

The stock change for a given DOM pool (i) is:

$$\Delta DOM_i = \sum_{j=1}^{n} d_{ji} S_j + \sum_{j=1}^{n} b_{ji} S_j + \sum_{k=1}^{q} a_k Ptki_{DOM_k} - a_k DOM_i$$

where

DOM_i is the total C stock of the ith pool,
d_{ji} is the proportion of a pool affected by a disturbance, S_j is the total C stock of the jth pool (either biomass or DOM), n is the total number of pools. When $i <> j$, then $d_{ji} S_j$ is positive and d_{ij} is the proportion of pool j transferred into the ith DOM pool, when $i = j$, then $d_{ii} S_i$ is negative and carbon is transferred out of the ith pool.
b_{ji} is the rate of biomass turnover or direct DOM transfers from the jth pool to the ith DOM pool, n is the total number of pools, S_j is the total C stock of the jth pool (either biomass or DOM). $d_{ij} S_i$ is negative when $j = i$ and carbon is transferred out of the ith pool.
a_k is the applied decay rate of the kth DOM pool, $P_{t\,ki}$ is the proportion of the decay from the kth pool that is transferred to the ith DOM pool, DOM_k is the total stock size of the kth pool, and q is the total number of DOM pools. This is a special case for aboveground slow DOM and belowground slow DOM pools only.
$a_k DOM_i$ is transfers out of the ith DOM pool due to decay where a_k is the applied decay rate of the ith DOM pool.

The total ecosystem stock change is

$$\Delta ECO = \sum_{j=1}^{q} \Delta DOM_j + \sum_{j=1}^{r} \Delta BIO_j$$

where, q is the total number of DOM pools, and r is the total number of biomass pools.

amount of N_2O is estimated as 0.00017 times the amount of CO_2.

The CBM-CFS3 provides a number of outputs useful for comparisons with field measurements or with estimates generated using other modelling approaches. Such comparisons can provide valuable insight into the model's ability to provide estimates of forest ecosystem C stocks and C stock changes, and also provide opportunities for model validation.

The CBM-CFS3 reports annual net primary production (NPP) for each type of stand simulated by the model. NPP is calculated as the sum of net growth (i.e. growth that results in positive increment) and growth that replaces material lost to biomass turnover during the year. In young, actively growing stands, a large proportion of NPP results in positive growth increment while in older, mature stands, a larger proportion of NPP is allocated to replacement of material lost to turnover. NPP is calculated in this manner because the CBM-CFS3 does not simulate photosynthesis and autotrophic respiration. NPP is a very important ecological concept, is a widely reported indicator, and is therefore a very useful indicator for making comparisons between estimates generated using the CBM-CFS3 and estimates generated using other models.

Chapin et al. (2006) define net ecosystem production (NEP), as gross primary production (GPP) minus total ecosystem respiration (ER). The CBM-CFS3 estimates NEP as NPP minus heterotrophic respiration (Rh), where Rh is the sum of all DOM pool decomposition losses to the atmosphere (P_{atm}). Neither GPP nor ER is estimated by the CBM-CFS3.

Fig. 12 illustrates the changes in NPP, Rh, net growth and biomass turnover as a stand grows undisturbed. The example stand used here is also described in terms of biomass stocks (Fig. 5). NPP increased rapidly as the stand grew to about age 70, after which it stabilized. Rh was high initially, as there were large amounts of DOM remaining after the stand-initiating fire. Rh dropped as the DOM stocks decreased and there were relatively low amounts of biomass turnover. As biomass turnover increased, Rh increased correspondingly.

In describing terms to represent the overall ecosystem C balance from all sources and sinks, two terms are recommended in the literature: net ecosystem C balance (NECB) for stand-level analysis on annual time steps, and net biome production (NBP) over regional or larger areas and multi-decadal time spans (IGBP, 1998; Chapin et al., 2006). These terms are equivalent to NEP plus changes due to disturbances. The CBM-CFS3 calculates the overall ecosystem C balance as the total ecosystem stock change (see Box 2), also called NBP. The user can determine the spatial scale from a single stand to a large landscape. In this calculation, the CBM-CFS3 includes the net growth increment and losses from the ecosystem due to decay (P_{atm}), due to atmospheric emissions caused by disturbances such as forest fires, and losses to the forest products sector. Losses as dissolved C are assumed to be included in the decomposition releases to the atmosphere.

Many forest ecosystem C models have been developed, especially in recent years. A number of these models employ a photosynthesis-driven approach to simulating biomass C dynamics that is fundamentally different from the yield-driven approach used in the CBM-CFS3. Instead of calculating biomass C increments as a function of yield data, photosynthesis-driven models simulate growth as a function of available photosynthetically active radiation, nutrients, water and the ability of different plant functional groups to produce biomass. Where estimates generated by yield-driven modelling agree with those generated by photosynthesis-driven modelling, this helps build confidence in both approaches and in the underlying data used by the models. Validation can be done by comparing NEP estimates generated by the models with ground-based estimates, such as at eddy covariance flux tower sites (Baldocchi, 2003). However, such measurements are expensive to obtain and are therefore only available for a very small number of sites. Moreover, these measurements have to be summed to annual totals prior to comparing with the annual CBM-CFS3 output. Comparisons between estimates generated using CBM-CFS3 and estimates based on flux tower measurements have been made by Trofymow et al. (2008) and similar comparisons are in progress at other sites maintained by the Canadian Carbon Program's Fluxnet-Canada Research Network.

The CBM-CFS3 outputs can also be used to compare the model's results with those generated by forest estate models. We have conducted extensive comparisons with forest management partners specifically comparing future forest

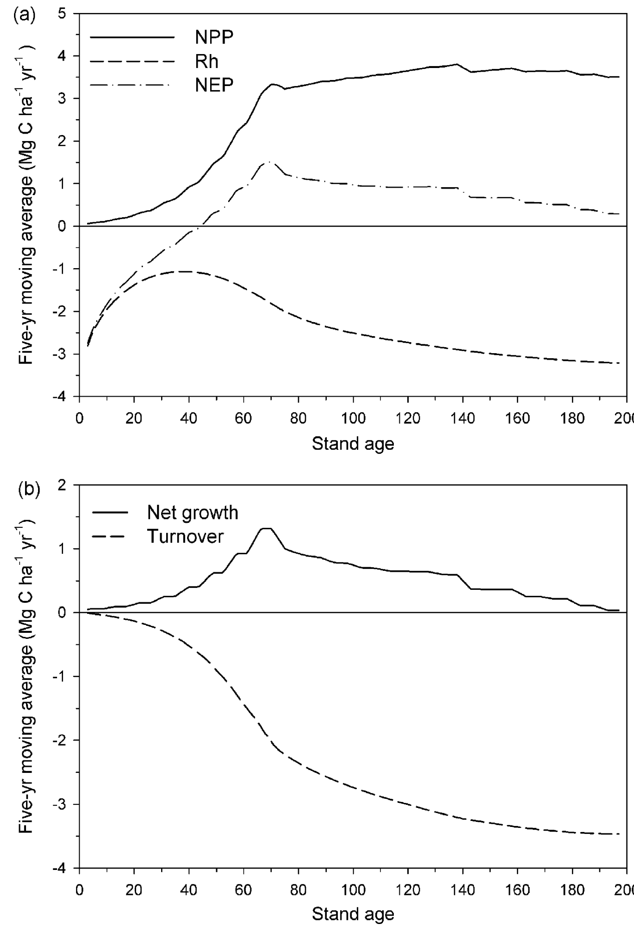

Fig. 12 – Changes in ecosystem indicators for example lodgepole pine stand. (a) Net primary productivity (NPP), heterotrophic respiration (Rh), net ecosystem productivity (NEP) (b) the two components of NPP: net growth and biomass turnover.

age–class distributions, distributions of other forest characteristics, trends in merchantable wood supply, and harvest efficiency in terms of volume yield per hectare. These comparisons, based on the same input data, helped to verify the model's ability to represent landscape dynamics as well as the forest estate models—which typically represent these dynamics in far greater detail than is possible in the CBM-CFS3. Although wood supply cannot be evaluated directly from the model outputs, general trends can be evaluated by converting the merchantable stemwood C pool to volume. This pool accounts for the C in both the stemwood and the stem bark, so conversion factors that take into account the ratio of wood biomass C to bark biomass C in the merchantable stem pool, the proportion of total wood biomass that is C, and the specific gravity of the wood must be applied to generate estimates of merchantable wood volume.

6. Discussion and conclusion

The CBM-CFS3 has been designed with a wide range of potential users in mind. These users, according to a recent survey of the CBM-CFS3 user community, include government and industry foresters, forestry consultants, environmental non-government organization analysts, and university researchers in Canada and abroad (e.g. Zamolodchikov et al., 2008). They are evaluating forest C dynamics for a variety of purposes, most commonly for assessing C stocks and future forecasting. A smaller number of users are also assessing impacts of disturbances and land-use change.

The model is most useful for calculating the C-implications of forest management activities and land-use change in upland, even-aged forested landscapes. Some suitable management scenarios include lengthening harvest rotations, shortening regeneration delays, or changing the species or provenance planted following harvest. Land-use change impacts such as deforestation and subsequent woody decay dynamics, afforestation of agricultural lands, or reforestation are also suited to analysis using the CBM-CFS3 as long as biomass dynamics from non-tree species are negligible. The model can also be used to calculate the C-implications of a GHG mitigation project by comparing simulations of business-as-usual and a change in management. The model is not suitable for simulating ecological restoration projects (e.g. afforestation of mining sites, wetlands or industrial lands), because the required information on soil C stocks or dynamics in those scenarios is lacking. CBM-CFS3 is also not suitable for agricultural, grassland or shrubland ecosystems (i.e. post-deforestation land uses) because the biomass dynamics in the model are driven by tree-derived parameters and the dead organic matter and soil dynamics have been calibrated using forest plot data only.

Presently available C models range from simple static carbon-inventory type models to complex models with hourly time steps and detailed parameterization of photosynthesis and soil nutrients.

The CBM-CFS3 is designed for applications that require an intermediate level of complexity. The annual time steps and explicit modelling of disturbances, management activities and land-use change provide considerable information for people interested in understanding spatial and temporal C-dynamics in their landscape. The generic framework links to timber supply datasets and requires fewer parameters than many process-driven models, making it easier to use for people interested in C-dynamics. The implementation of international accounting rules and land-use accounting flags provide an added benefit for users interested in C-reporting, forest certification or offset trading. Future advancement of the model will focus on adding the fate of harvested forest products and taking global change factors into account for both growth and decomposition processes.

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