The Role of Canadian Forests in the Global Carbon Budget

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An assessment of the contribution of Canadian forest ecosystems and forest sector activities to the global carbon budget has been performed for the reference year 1986. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) was developed as a spatial and temporal framework for integrating best-available data for carbon stored in forest biomass, soils, peatlands and forest products. These data, combined with simulation of forest dynamics, provided estimates both for Canadian forest sector carbon pool sizes and for the net changes in these pools during the reference year. Both continuous processes (growth, decomposition,etc.) and discrete, event-specific processes (disturbances, including wildfire) are explicitly represented and inferred from existing data. A net atmospheric sink of approximately 77 Mt C was estimated for 1986. The results strongly indicate the importance of including the interactions between, and changes in, all those forest sector carbon pools which are vulnerable to change over the time scales of interest. Sensitivity analysis indicates that the 1986 net sink is unstable with respect to changes in disturbance regimes which can be expected in a changing climate.

Introduction

Scientific attention has recently focussed on the role that circumpolar forest ecosystems play in the global carbon cycle (e.g., Kauppi et al. 1992, Apps and Kurz 1991, Gorham 1991, Harmon et al. 1990, Schlesinger 1990, Tans et al. 1990, Woodwell 1989) In particular, Tans et al. (1990) advanced the controversial hypothesis that northern forests are the 'missing carbon sink' – i.e., the latitudinal distribution of sinks required to balance anthropogenic emissions with observed atmospheric increases (Houghton et al. 1983). Alternative mechanisms have been proposed to account for this missing carbon (e.g., Broecker and Peng 1992, Sarmiento and Sundquist 1992), but the size of the boreal forest carbon pools, together with the potential for human-induced changes in them, provides strong motivation for improving our quantitative understanding of the uptake, storage, and release of carbon by these systems.

Canadian forests comprise some 30% of the global circumpolar boreal forest. The purpose of this paper is to present an integrated approach to the assessment of the part that these forests play in the global carbon cycle. The aim of this assessment is not merely to provide a status report on the current carbon pools and fluxes but also to provide a conceptual structure and model to assess the vulnerability of these pools and

1993. In: "Carbon Balance of World's Forested Ecosystems: Towards a Global Assessment." IPCC Workshop. Joensuu, Finland fluxes to change over the next 50 to 100 years. It is important to asce the boreal forest contributes to the 'missing sink'. It is, however, perh to determine how carbon cycling processes may change in the fu human intervention or changes in climate. If the forests today do i carbon sink, is there any reason to expect that they will remain a sin negative or positive feedback to the enhanced greenhouse effect? A resource management actions society can take (or avoid) to ensure negative or reduction in the positive feedbacks? The answers to thes more than a static inventory and budget: the potential for changes i i.e., ecosystem dynamics – must be taken into account. Accoun dynamics requires that the critical processes1) and controls that r changes within the forest ecosystem and with the atmosphere be ex

The structure of the Carbon Budget Model of the Canadian Forest has been designed with three fundamental principles in mind: 1 maximum extent possible, use actual, observed data, 2) it should main carbon pools and the exchanges of carbon between them a phere, and 3) it should permit the examination of future scenarios of resource management. This last design principle is aimed at pro procedure for exploring the sensitivity, or vulnerability, of Canadian f pools to future change. In the absence of data from controlled exp methods are probably the best, if not the only experimental tools investigations (Shuttleworth 1992). The assessment of current con fluxes) provides a starting point for projecting future carbon bud alternative scenarios of future climate and resource management p

In the sections that follow, some basic information on the impo forests will be provided, followed by an overview of the conceptual s CFS, a review of the data and results for the Phase 1 assessment (as CBM-CFS12)) for a reference year 1986. The paper will conclude several sensitivity analyses with the CBM-CFS which indicate the role that disturbances3) play in determining both contemporary and ets.

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1) Critical processes in the current context are those that satisfy two criteria: 1) they p function in system carbon dynamics and 2) there is reason to expect that their role the time period of interest.

2) The acronym CBM-CFS1 will be used to refer to model attributes, data, or results t driven phase 1 assessment of the reference year 1986. The acronym CBM-CFS is carbon budget modelling framework and more general concepts.

3) For the purposes of this paper, a disturbance is defined as an event, discrete in tim by forces external to the ecosystem, which has a short-term, but acute, impact a responds, often over much longer time periods. Examples include wildfire (anthropogenic).

Canadian Forests and Forestry

Canada is a forest nation, and forestry activities have a significant influence on her economy. About 45% (453 Mha) of the land area are covered in forest. Of these, 233 Mha are classified as 'productive' forests containing an estimated volume of 24.6×10^9 m^3 (Honer et al. 1991). In 1990, harvesting of the managed portion of Canada's forests produced 112 Mt dry weight of wood fibre, contributing significantly to the Canadian economy. The total value of forest product shipments was $ 44 billion, contributing more than $ 20 billion to the Canadian economy – more than fishing, mining, and energy sectors combined (Forestry Canada 1990). Forestry, therefore, plays a significant role in the contemporary Canadian way of life.

Forestry activities also influence the forest environment. They are a factor in determining the structure and function of certain parts of the Canadian forest through harvesting, silviculture and forest protection measures. In comparison with European forests, only a small fraction of Canada's forest area has been directly affected by forestry activities. Carbon flows associated with Canadian forestry activities, however, are not insignificant and should be considered when evaluating Canada's contribution to the global carbon cycle. Environmentally-sound resource-management policies, which balance economic needs with environmental considerations (including climate change feedbacks), have become increasingly important in Canadian forestry (Maini 1990). Predicting changes in Canadian forests, and their future carbon budget contributions, is therefore more than an interesting scientific challenge for Canadians.

The forested landscape of Canada is a complex spatial assemblage of forest types (Rowe, 1972) that have evolved since the time of the last glaciation (ca. 10 Kyr BP) in response to changing climatic and geomorphological conditions. Ten Ecoclimatic Provinces (EPs), each of which "*are characterised by distinctive ecological responses to climate, as expressed by vegetation and reflected in the soils, wildlife and water*" (Ecoregions Working Group 1989), have been described for Canada's land area. This spatial classification has been used for recent studies on climate change impacts (Zoltai 1989, Rizzo and Wiken 1992) and provides the spatial structure of the CBM-CFS. For the purposes of the carbon assessment, the boreal forest EP was further differentiated into a (moist) western boreal forest and a (dry) eastern boreal forest (Fig. 1, Table 1).

The current Canadian landscape is dominated by the boreal forest (Fig. 1) which, in Canada comprises primarily conifers (characteristically the spruces and pines: *Picea glauca*, *P. mariana*, and *Pinus banksiana*) with an admixture of broad-leaved hardwoods (particularly aspen, balsam poplar and white birch: *Populus tremuloides*, *P. balsamifera*, and *Betula papyrifera*). The boreal forest EPs are a complex spatial mosaic of upland and lowland forests whose functioning and spatial structure has been strongly influenced by frequent natural disturbances.

In these northern forests, the carbon content of the soils, including the forest floor and coarse woody debris, can equal and exceed that of the phytomass (Table 2). The litter, coarse-woody debris, and soil organic matter C pools are affected by changes in the overstory stand conditions as well as by disturbances, and the dynamics of these pools must therefore be included in C budgets and inventories.

No.	Ecoclimatic Province	Area in inventory ('000 ha)	bic
1	Arctic	3,499	
2	Subarctic	136,439	
3	Boreal West	114,663	
4	Cool Temperate	35,584	
5	Moderate Temperate	2,082	
6	Grassland	6,127	
7	Subarctic Cordilleran	14,733	
8	Cordilleran	90,676	
9	Interior Cordilleran	19,381	
10	Pacific Cordilleran	20,605	
11	Boreal East	134,483	

Fig. 1. Ecoclimatic Provinces of Canada (adapted from Ecoregions Wo
The Boreal forest Ecoclimatic Province has been divided into an ea
western (No. 3) section to reflect differences in moisture conditions.

Table 1. The vegetation development characteristics of the different Ecoclimatic Provinces.

Ecoclimatic Provinces	Vegetation development	Characteristic tree species
Arctic	Treeless, with tundra, polar semi-desert, or polar desert	-
Subarctic	Open-canopied conifer woodlands, with tundra patches	black spruce
Boreal East	Closed-canopied forests of conifer or mixed conifer-hardwood	black spruce, white spruce, balsam fir, white birch
Boreal West	Closed-canopied forests of conifer or mixed conifer-hardwood	black spruce, white spruce, trembling aspen, jack pine
Cool Temperate	Mixed forests of shade-tolerant hardwood-conifer	red spruce, white spruce, white pine, balsam fir, hemlock, maples, birch, ash, beech, aspen, oak
Moderate Temperate	Deciduous forests	maples, beech, oaks, walnut, elm, cottonwood, balsam poplar, tulip tree, hickory
Grassland	Grassland with or without small groves of hardwood trees	trembling aspen
Subarctic Cordilleran	Open-canopied conifer woodland and alpine tundra in elevational zones	white spruce, paper birch, balsam poplar, trembling aspen
Cordilleran	Closed-canopied conifer or mixedwood forests, open-canopied conifer woodland, and alpine tundra in elevational zones	white spruce, black spruce, Engelmann spruce, lodgepole pine, alpine fir, trembling aspen, balsam poplar, tamarack
Interior Cordilleran	Grassland (with or without scattered trees), closed-canopied conifer or mixedwood forest, open-canopied conifer woodland, and alpine tundra in elevational and rain shadow zones	Douglas fir, lodgepole pine, ponderosa pine, white spruce, black spruce, Engelmann spruce, alpine fir, subarctic fir, birch, aspen
Pacific Cordilleran	Closed-canopied conifer forest, open-canopied conifer woodland, and alpine tundra in elevational zones	Douglas fir, amabilis fir, western hemlock, mountain hemlock, sitka spruce, alpine fir, yellow cedar, western red cedar

Table 2. Relationship of Carbon in biomass and soil pools for World ec Schlesinger 1977).

Ecosystem	$C_{soils}/C_{biomass}$
Tropical forests	0.55
Temperate forests	0.81
Boreal forests	1.66
Swamp and marsh	10.0
Temperate grassland	27.5
Tundra & alpine	43.0

Extensive regions of wetland and peat-accumulating formations are out the forests of Canada. Canada contains approximately 35% of tl (Kivinen and Pakarinen 1981). In these wetland systems the living bi only a very small fraction (ca. 1.5%, Gorham 1991) of the total carbc peatland areas in Canada are found in the flat topography associa and western portions of the boreal and subarctic EPs (National Wetl 1986) with the second largest peatland area in the world being in the lowlands of central Canada. The functioning (atmospheric exchang as well as the spatial distribution of these peatlands is currently imp (Gorham 1991). Nevertheless it is clear that these pools are highly vu through human intervention (e.g., drainage to improve forest timber sively practised in Finland) or because of climate change (Hogg et Vitt 1990, Gorham 1988).

CBM-CFS: Carbon Budget Model of the Canadian Fo

The CBM-CFS uses an integrated ecosystem approach that incorp carbon pools and the processes that control transfers (fluxes) bet done within a spatial representation that reflects the essential ecolo of the Canadian forests and allows biologically meaningful summa scape. It accounts for changes in soil and litter as well as in vegeta ecosystem production (NEP) and not merely net primary productic Apps 1992a). The complex role played by disturbances, both natural is explicit in the dynamic assessment.

The model also accounts for the carbon removed from the forest vested material. The CBM-CFS has been designed to permit exami strategies for increasing forest productivity (e.g., through silvicultural ing carbon releases (e.g., using long-lived forest products, bioener silvicultural procedures for optimising soil carbon retention).

By including all significant and potentially vulnerable carbon pools, individual component contributions into perspective. Focussing to components of the whole system is an easy, but dangerous, trap to fall into without such perspective. The relative ease with which aboveground biomass data may be acquired tempts the use of changes in biomass production, or even commercial timber volume, to assess changes in carbon sequestration (e.g., Kauppi et al. 1992). For northern ecosystems, which have significant quantities of carbon tied up in dynamic detrital and soil pools, calculations that ignore soil and detrital dynamics or disturbances can lead to erroneous carbon budget projections and inappropriate resource management decisions.

The CBM-CFS deals with the forested landscapes of Canada and human activities that influence the transfers of carbon within and from these systems. The model focusses on a time horizon of 100 years with a time resolution of one year. The first phase assessment (CBM-CFS1) is further restricted by data availability (see below) to the analysis of a single reference year (1986) but the structure has been designed for dynamic simulations of future scenarios.

Spatial Integration

The forests of Canada are divided into Ecoclimatic Provinces as described in above (Fig.1). The intersection of the EPs with the 12 administrative provinces and territories, provides the 41 basic spatial units for the analysis. Within each spatial unit, various forest types are defined according to a set of indices (classifiers) that are derived from a national forest inventory (Bonnor 1985). These classifiers include: productivity class, stocking, cover type (hardwood, softwood, mixedwood, undetermined), age class, and site quality. The areal extent and age class distribution of each forest type within each spatial unit can be derived from the forest inventory information for that unit. Different forest types have different growth characteristics that also vary with the spatial unit. These growth characteristics are defined by biomass-over-age curves and are one of the major determinants of ecosystem dynamics over the short (100 year) term.

The total area and the age-class distribution of each forest type within each spatial unit **i**, combined with the growth curve information, are used to estimate biomass carbon and its annual increment:

$$C^{i}_{\mathrm{biomass}} = \sum_{\mathrm{type}} (C/\mathrm{ha})^{i}_{\mathrm{type}} \times \mathrm{AREA}^{i}_{\mathrm{type}} \tag{1}$$

$$\Delta C^{i}_{\mathrm{biomass}} = \sum_{\mathrm{type}} (\Delta C/\mathrm{ha})^{i}_{\mathrm{type}} \times \mathrm{AREA}^{i}_{\mathrm{type}} \tag{2}$$

where the index **type** refers to forest type, $\mathbf{AREA}^{i}$ is the area of that forest type in spatial unit **i**, $(\mathbf{C/ha})^{i}$ is the biomass (phytomass) carbon density and $(\Delta\mathbf{C/ha})^{i}$ the annual increment, both derived from the biomass-over-age curve for that forest type.

Different forest floor and soil carbon densities are associated with each such spatial unit and forest type. These densities explicitly include detrital material and coarse woody debris. Their dynamics reflect the Ecoclimatic conditions (Ecoclimatic Province), the site conditions (forest type) and the stage of forest stand development as will be further described below. The pool sizes and annual changes in them are aggregated across the

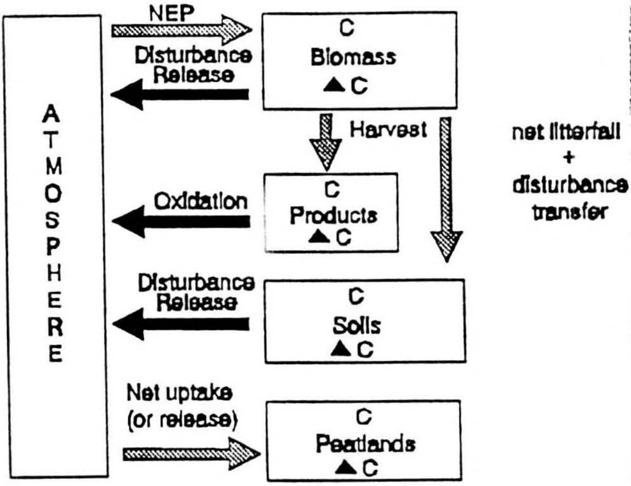

Fig. 2. Carbon pools and transfers within each forest type. The pool increments (shown in each box as C and ΔC, respectively) for a give calculated using equations [1] and [2] and then summed over all spatia national values. Transfers between pools are due to both continuou growth and decomposition) and event-specific disturbances as disc Exchanges with the atmosphere are inferred from the net changes i assuming conservation of mass (carbon).

landscape in the same way as for biomass (equations 1 and 2). In approach should be used for the accumulation of carbon in peat; in pr of data required a simplified approach in Phase 1, which will be discu

Forest Ecosystem Pools and Processes

Ecosystem carbon dynamics are expressed as *net* changes in the car the integrated result of carbon fluxes (transfers) between pools an phere. Fig. 2 is a simplified representation of the main carbon pool more detailed diagrammatic representation of the conceptual model trols is given in Kurz et al. (1991,1992).

The biomass compartment includes all overstory phytomass in both belowground components[4]. The soil box in Fig. 2 comprises three represent carbon stored in both detritus (including woody debris) and s For each forest type and spatial unit, these three soil pools are cha turnover rates (fast: 3–20 year, medium: 20–100 year, and slow: 100+

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[4] Due to lack of available data, belowground biomass is not included in the Phase 1 biom further on. Fine root turnover, however, is incorporated in the soil pool dynamics. A c of belowground dynamics, essential for climate change scenarios, is currently being tes in a subsequent manuscript (Kurz and Apps 1992c).

thought of as two detrital pools (fast and medium) and a soil organic matter pool (slow). The fast pool receives fine litter input (aboveground and belowground) while the medium pool receives coarse biomass litterfall, thereby accounting explicitly for coarse woody debris dynamics. Decomposition of the fast and medium pools releases specified fractions of the carbon to the atmosphere and transfers the remaining carbon to the slow pool as humified material.

Annual changes of these soil pools, in the absence of disturbances, are calculated from the net balance between biomass inputs and decomposition outputs; this difference is expressed as net litterfall (Fig. 2). The soil carbon pool increment (ΔC, Fig. 2) also includes changes associated with disturbances as discussed below. Both biomass inputs and decomposition rates are allowed to vary with spatial unit and forest type. Within a given forest type, changes in the soil pool are also dependent on the stage of vegetation development, linking soil and biomass dynamics in two ways. First, inputs to the fast and medium pools depend on litterfall and stem mortality. Both litterfall and stem mortality are strong functions of the stage of stand development and increase substantially, for example, during stand breakup in late stages of development. Secondly, the decomposition rates of the two detrital pools depend on the biomass state through changes in exposure with changes in canopy cover.

Inputs to the slow pool depend on the size of the detrital pools and their decomposition rates. Following Schlesinger (1990), the soil organic matter content is assumed to change very slowly under constant (or slowly changing) environmental conditions – on a time scale of many centuries. The decomposition rate of the slow pool is calculated in a way that ensures that over the course of a natural rotation (100–300 years, depending on the spatial unit and forest type), an approximate steady state is obtained for the slow soil pool. As a result, the time-averaged slow pool size does not change appreciably unless the period between successive disturbances changes substantially from the current natural rotation (see Kurz et al. 1992 for details).

Ecosystem pool levels are regulated by the processes that control the flow of carbon between them. This flow begins with uptake from the atmosphere through photosynthesis and concludes when the carbon is returned to the atmosphere or transferred to completely inert pools (Kurz et al. 1991). Photosynthesis uptake is shown in Fig. 2 as single arrows representing NEP for forests and peatlands (Apps and Kurz 1991; Kurz and Apps 1992a). The subsequent redistribution of carbon to other pools and return to the atmosphere is controlled by processes which, depending on their spatial and temporal characteristics, can be represented by either continuous or event-specific and discrete approximations. The concepts of 'discrete' and 'event-specific' are scale dependent – i.e., depend on the temporal and spatial resolution at which the processes are viewed. What can be approximated as a continuous change at the stand level (e.g., biomass growth) is more lumpy at the individual tree (e.g., mortality) and the needle (e.g., litterfall) levels. The delineation used for the CBM-CFS is appropriate for the spatial and temporal resolution needed for biome-level national analyses.

The CBM-CFS treats growth, litterfall, respiration, and decomposition as continuous processes and disturbances as discrete and event-specific. The continuous processes result in relatively smooth changes in ecosystem state variables over time and produce similarly smooth changes across the landscape. Event-specific, disc have characteristically different spatial and temporal dynamics. They with aperiodic disturbances (e.g., wildfire, insect and disease outbreaks, which act as cataclysmic events at the level of individual ecosystems bances are characterised by a step function (discrete) response (e.g., living biomass in a forest stand by fire) followed by a delayed, gradual r ecosystem adjusts to the new conditions. This delayed response may b of an earlier stage of seral succession (e.g., for example aspen regene fire in a spruce stand in boreal mixedwood forest types), or can set the e entirely new trajectory more adapted to a changed environment (e.g., Sh 1980; Overpeck et al. 1990). Disturbances also introduce abrupt anc features in the spatial pattern. Changes in land-use are readily represer approach.

The CBM-CFS recognises five different disturbance types which are important for Canadian forests: wildfire, insect-induced stand mortality, of forest harvest (clear-cut, clear-cut followed by slashburn, and se These disturbances are characterised by disturbance matrices which sp fers of ecosystem carbon at the time of disturbance and by rules wh allocation of the specified annual disturbances across spatial units and f Kurz et al. 1992 for more details). This approach permits the disturbanc and disturbance matrices) to be specified by actual data (as in the phas or by scenario-based assumptions.

The explicit inclusion of disturbance has important consequences for th budget. Disturbances not only release carbon directly to the atmos transfer carbon from biomass to the detrital and soil pools (Fig. 2). regulated systems, these transfers may be very important for the future ics. The results of Phase 1 support this hypothesis. For example, fire stand mortality, and harvesting play different roles in the dynamics o debris (Harmon et al. 1986), but the existence and dynamics of this ignored (Mark Harmon pers. com. Oct. 1991).

The explicit representation of disturbances is essential for the sca temporal (e.g., Overpeck et al. 1990) and spatial (e.g., Holling 1992) r ecosystem level to the landscape or biome level. Such cross-scale inte the role of disturbances in determining the structure (e.g., spatial patter distribution), and subsequent function (e.g., NEP) of these forest e abrupt redistribution of ecosystem resources followed by a 'resetting' c to an earlier stage of succession or onto a new trajectory may be an ir eration in future climate scenario projections.

Peatlands

Peatland dynamics are strongly influenced by the hydrological regi Bellamy 1974, Clymo 1984). Peat formation takes place in waterlog oxygen diffusion is inhibited, generating a complex chemical enviro anaerobic conditions in the catotelm. Under such conditions, decomposition is severely impeded. Peat accumulation occurs when inputs of biomass detrital material moving from the aerobic acrotelm into the catotelm, exceed the decomposition losses from the submerged column. Vegetation growing on such wetland sites must obviously be tolerant and adapted to waterlogged soils. Such areas are dominated by mosses, sedges, shrubs, and tree species such as black spruce (*P. mariana*) and tamarack (*Larix laricina*) in open canopied woodlands. In general, trees play a secondary role in the NPP of these wetlands.

In principle, the process of peat formation can be considered as a special case of the soil pools discussed in the previous section, characterised by different decomposition rates and different proportions of CH_4 and CO_2 releases. The CBM-CFS initially defined waterlogged analogues of each of the three soil pools using decomposition-rate multipliers (Ecoclimatic-province specific) and emission factors (CH_4/CO_2) in order to explore the effects of changes in water table due to drainage, flooding, or climate-induced changes. This would be simulated by moving submerged pools to nonsubmerged ones and changing the multipliers appropriately. This process-oriented approach was temporarily abandoned for the CBM-CFS1 because of data limitations (see sections on data below).

Although both processes may occur simultaneously at the same location on the landscape, the accumulation of carbon in peat is assumed to occur independently from accumulation of carbon in forest soils in the CBM-CFS. In contrast to the simulation of forest soils described above, however, peat column dynamics are not coupled to the biomass dynamics in the Phase 1 model. Instead, the average annual net carbon uptake by peat (as well as methane release) is simply combined with area estimates of peatlands for the 41 spatial units. Fig. 2, therefore, shows only the net accumulation of carbon by the peatland pool. The carbon contained in peatlands may be calculated in a similar manner by multiplying the average carbon density by these same area statistics (Gorham 1988).

Forest Sector Pools and Processes

Explicit representation of human influences on the global carbon contributions of Canadian forest systems was one of the prime design considerations of the CBM-CFS. Human activities can directly influence the overall forest-sector carbon budget in a number of ways, including:

i. land-use decisions, forest protection measures, and harvesting, which influence both the structure and function of the forests;
ii. active silvicultural management (which changes the functioning of individual forest ecosystems);
iii. carbon emissions (e.g., fossil fuel use, fertiliser production) associated with the various forest sector activities;
iv. offset of fossil fuel use by forest bioenergy, and replacement of high-energy-content products (such as aluminum, steel and concrete) by wood products;
v. storage of carbon in products derived from harvested forest biomass;

vi. disposal and recycling of forest products and landfill manageme

The CBM-CFS structure has been conceptually designed to evaluat integrated manner (Kurz et al. 1991), either using actual data (retros with scenarios (sensitivity and projective analyses). Changes in f function associated with active forest management (items 1 and 2 representation of the biomass, soil, peatland, and disturbance d above. The other considerations are handled within a forest product

The estimation of carbon transfers associated with products derived is based on conservation of mass (carbon) and involves sever biomass carbon annually removed from Canadian forests is determi unit, Fig. 2) from forest harvest and forest product data statistics. tracked as an annual cohort through a series of product conversions it is either released to the atmosphere through combustion an sequestered in a slowly decomposing end-use pool, such as landfill. profile, which also specifies the proportion of CO_2 and CH_4 released is associated with each use-category. Recycling options may be ex product sector module by returning forest products to use-categories ing of them. Bioenergy options can be analyzed by allocating bio products to energy production.

The estimation of annual carbon release to the atmosphere from sector pool (Fig. 2) requires an estimation of the contemporary fores The forest product module was used to simulate harvesting, proces forest products for the period 1947 to 1986. For the 1986 analy simulates 40 annual cohorts of forest products and sums their indivi that year's carbon exchange. In Fig. 2, the inputs to the forest sector 1986 harvested biomass but the release to the atmosphere include previous (39 year) cohorts as well as releases from 1986 harvest 1992).

Data for CBM-CFS1: Analysis of 1986 Carbon Budge

The CBM-CFS uses 5 types of data that define: 1) the spatial analysis; 2) biomass pools and biomass dynamics; 3) soils and de dynamics; 4) forest product sector pools and processes, and 5) d The spatial representation in the CBM-CFS is based on the Eco Canada discussed above (Fig. 1) and the following paragraphs dis the other data for the CBM-CFS1 phase 1 model (see also Kurz et

Biomass Data

Biomass growth dynamics and pool sizes were developed from d Canadian Forest Resource Data System (CFRDS) (Gray and Ni 1991). This data system contains both Canada's 1986 forest invento

1988) and an inventory of Canada' forest biomass (Bonnor 1985) that in turn is based on an earlier forest inventory (Bonnor 1982). The 1981 inventory contains more than a million records distributed over some 50,000 spatial cells.

These data were regrouped into the 41 spatial units of the CBM-CFS and used to determine the distribution of the different forest types used by the model. This aggregation gives up spatial information but retains information about the areal distribution of each of these forest types within each spatial unit, allowing the use of weighted summations of biomass carbon and exchanges within these units (equations 1 and 2). Biomass dynamics for the various forest types were inferred directly from the CFRDS age-class information by using them to generate a set of (aboveground) biomass-over-age relationships for both the softwood and hardwood components of each forest type (see also Kurz et al. 1992).

Canada's biomass inventory (Bonnor 1985) also apportions biomass to different aboveground biomass components according to size (merchantable stems, merchantable foliage, other merchantable biomass such as branches, tops and stumps and submerchantable trees. These data are retained in the CBM-CFS and, together with the biomass-over-age curves, are used to estimate net litterfall inputs to the detrital soil pools (see below). For the CBM-CFS1 phase 1 estimates (Apps and Kurz 1991; Kurz et al. 1992), representation of belowground biomass dynamics was restricted to fine-root turnover because root data are not contained in the CFRDS files.

This data-intensive approach has several limitations. Roughly equivalent to a chronosequence approach (Kurz et al. 1992), it has acknowledged predictive shortcomings (Kimmins 1985, Apps et al. 1992) for future carbon budgets but probably provides the least biased estimate of contemporary dynamics possible with the existing CFRDS data. It should be pointed out that any changes in past growth conditions (due to changes in climate, for example) are deeply and inextricably buried within these data. The growth dynamics used in the CBM-CFS1 makes no attempt to resolve, or detect, such influences.

A second limitation arises because of missing data. Biomass dynamics can only be inferred for those parts of the Canadian forest estate for which biomass inventory data exists; uninventoried areas are necessarily treated as 'carbon neutral', although they are recognised within the model structure. Of the 578 Mha in the CFRDS spatial inventory, 404 Mha (76%) have biomass values attached and are therefore represented in the model. Most of the remaining area is unproductive and unstocked land at the margins of the forested estate. Treating these areas as carbon neutral is therefore not expected to introduce significant bias in the Phase 1 estimates. The importance of these areas, however, could be greatly increased in the future if productivity and forest cover change in response to climatic changes.

Soils Data

The primary source of data initially used for the soil carbon pool was the Oak Ridge National Laboratory (ORNL) global data set (Zinke et al. 1986). This database consists

Table 3. Initial values for the slow soil C pool. Data from Zinke et al. (198 average soil C contents for the Ecoclimatic Provinces.

Ecoclimatic Province	Soil C content kgC m^{-2}	Sample size n[a]	Standard error o the mean
1 Arctic	17.1	12	4.7
2 Subarctic	33.8	9	9.6
3 Boreal West	11.8	51	1.5
4 Cool Temperate	9.2	3	1.1
5 Moderate Temperate	8.4	2	2.7
6 Grassland	4.9	1	-
7 Subarctic Cordilleran	33.8[b]	-	-
8 Cordilleran	13.8	20	3.0
9 Interior Cordilleran	26.7	4	11.3
10 Pacific Cordilleran	12.7	15	3.0
11 Boreal East	11.8[c]	-	-

a) Seven data points indicating C contents from 100 to 450 kg C m^{-2} have been excl assumed to represent peatland C content.

b) Same data used for Subarctic Cordilleran and Subarctic.

c) Same data used for Boreal East and Boreal West.

of a set of point data with relatively poor coverage for northern Cana the CBM-CFS1 because it was, at the time[5], the only available, comp having the required national scope. For use within the CBM-CFS, th aggregated to the level of Ecoclimatic Province (Table 3).

The ORNL database was assembled with a stated objective of " *organic carbon pool under relatively undisturbed soil conditions*" (Because this assumption is likely inappropriate for the forests of Cana how the CBM-CFS uses these data is in order. The amount of carbo balance between inputs of organic material from biota and losses d respiration (Fig. 2). The carbon content at a particular site therefo history of forest vegetation and its productivity at that site. Over lo carbon storage can slowly vary due to changes in climate, geolo vegetation succession. The time-integrated influence of these proces the variations of carbon storage across the landscape and is assume first order approximation, by the spatial representation used in the C On the shorter term, however, the changes in carbon transfers and v resulting from disturbances can cause significant fluctuations of the l (Zinke et al. 1986). These short-term variations could be importa disturbance-regulated forests of Canada. The CBM-CFS1 attempts

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[5] Subsequently, a more comprehensive Canadian data set has been collected (Ap unpublished data) and comparison of CBM-CFS results with this new data and communicated in a future manuscript (Apps, Kurz and Mair, in prep.)

by 'calibrating' the soil pools in a three pass simulation in which the disturbance and subsequent dynamics of biomass and soil C pools are simulated. For the CBM-CFS1 standard run, the simple assumption was made that all stands originated from wild fire.

Additional data which describe the dynamics (inputs and outputs) of the fast and medium soil pools are required by the CBM-CFS. Most of these data are anchored in results from studies performed on specific ecosystems in a relatively narrow range of successional stages and disturbance regimes (Edmonds 1984; Gessel and Turner 1976; Harmon et al. 1986; McClaugherty et al. 1984; Moore 1989; Piene and Van Cleve 1978). Other relevant studies reporting averages for larger geographic regions (Bray and Gorham 1964; Emanuel et al. 1984; Vogt et al. 1986) were also used. In addition to these published references, professional judgement and unpublished data (Mark Harmon pers. com. December 1989, Tony Trofymow pers. com. January 1990, Ole Hendrickson pers. com. January 1990) have been used to identify parameter values appropriate to the range of conditions found in Canada.

Forest Sector Data/Harvest and Forest Product Data

The forest sector module requires data of four types: annual harvest levels, partitioning (branching ratios) of carbon flows through the various use-categories, carbon retention times in these use-categories, and energy use (and source of energy) in the forest sector. Data for 1986 harvest levels and branching ratios were largely drawn from databases maintained by Statistics Canada and Forestry Canada and augmented, where necessary, by expert and professional advice. Carbon retention profiles were developed in an expert workshop and are largely based on professional judgement. Concurrent with the Phase 1 assessment, a study of the Canadian forest sector energy use on a national scale was initiated but these data were not available during the phase 1 assessment (Luce et al. unpublished data). Consequently, the CBM-CFS1 results presented do not include carbon releases associated with fossil fuel energy use. They do include, however, C released through the burning of forest products for energy production or waste.

Historic harvest volumes, required for estimation of carbon in forest product sector pools accumulated since 1947, were obtained from Statistics Canada records. Changes in the partitioning of harvested biomass to product types and other partitioning ratios (production efficiency, new pulping technology, and a shift to saw-chip use for pulp) over the period 1947-1986 were included in these simulations.

Disturbance Data

The CBM-CFS recognises 5 different disturbance regimes: wildfire, insect-induced stand mortality[6)], selective cutting, clear-cut harvesting and clear- cut harvesting fol-

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[6)] Only insect infestations resulting in extensive mortality and resetting of successional processes are treated as disturbances. Endemic insect damage, which may retard annual growth, is reflected in the biomass growth curves.

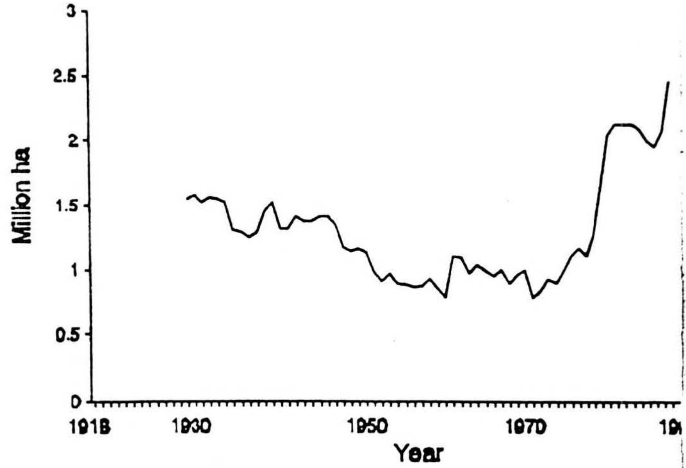

Fig. 3. Forest area burned 1918–1989 as a 10-year running average. (Data
1988 and Flannigan and van Wagner 1990).

lowed by slashburning. Distinction is required between the last two ha
because of the different timing of carbon release: slashburning resu
release of some biomass carbon to the atmosphere rather than transfe
the forest floor with a delayed release through decomposition. Data re
these disturbance types includes: elements of the disturbance matrice
redistribution of ecosystem carbon; the definition of extent (area) of ar
for each spatial unit; and rules defining the distribution of the area affe
different forest types in the disturbed spatial unit.

Data for wild fire and slashburning disturbance matrices, and rules fo
disturbances to the 41 spatial units were developed in consultation with
fire scientists (B.J. Stocks pers. com. May 1990, B. Lawson pers. con
were based on published and unpublished data, and where required, e
The decadal average (1980–1989) was used for the CBM-CFS1 as
because of the large fluctuations in annual wild fire levels (van Wa
decadal average (2.5 Mha/yr) is significantly higher than any prior 10-y
fire records were initiated in 1918 but is well below the peak year on r
1989). The effects of changing disturbance rates is one of the factor
sensitivity analysis discussed later.

Although Canada maintains an extensive Forest Insect and Disea
program, insect-induced mortality data were not available for the refe
Instead, the five-year-average volume loss due to insect disturba
period 1977–1981 (Honer and Bickerstaff 1985), were used as surro
ance with definition of disturbance matrices and allocation of disturba
CFS1 spatial units was provided by Forestry Canada scientists (J.
February 1990).

CBM-CFS1 results for reference year 1986

Table 4 and Fig. 4 show the results obtained for the reference year 1986. The biomass pool (12 GtC) shows a net decrease of 28 MtC, due primarily to disturbance transfers out of the pool (44 MtC to forest products, 20 MtC to the atmosphere, and 55 MtC to the forest floor). The forest floor and soil pools, estimated at 76 GtC, gained 57 MtC largely from disturbance inputs (55 MtC). The soil pool also released 15 MtC through disturbances, primarily wildfire (slashburning contributed an insignificant 0.88 MtC). Similarly the forest product sector pool, estimated at 0.6 GtC, gained 21 MtC after accounting for 23 MtC lost to oxidation and 44 MtC inputs from 1986 harvesting. The peatland pool, estimated to contain 135 GtC, accumulated an additional 26 MtC. The CBM-CFS1 results therefore suggest that Canada's forests represented a weak net sink of atmospheric carbon of the order of 77 MtC.

The net budget represents a very small change in the total carbon inventory of Canadian forests. In total, the change for forests and forest products sector is of the order of +0.6 %. This drops by an order of magnitude if peatlands are included in the calculation of total pool size. Table 5 shows the net change of the various pools as a percentage of their estimated size. The forest product sector, although a comparatively small pool, may represent an important sink and is one whose dynamics society can directly control.

Discussions of the results for specific regions (boreal forest, west coast forest and national forests) are provided elsewhere (Apps and Kurz 1991, Apps et al. 1992, Kurz and Apps 1992a, and Kurz et al. 1992).

Disturbances play multiple roles in the CBM-CFS1 carbon budget. In addition to the releases to the atmosphere, disturbances were responsible for significant redistribution of carbon within forest ecosystems (Table 6). These can be expected to influence the carbon budget of subsequent years. The role of disturbances in influencing the age-class structure has already been mentioned. The importance of the age-class structure to the carbon budget results will be further commented on in the last section.

The importance and influence of different disturbance types varies with the spatial unit. For example, in the drier western Boreal forest, wildfire is by far the dominant disturbance influencing both soil and atmospheric carbon transfers; in the moister Eastern boreal forests transfers to the soil pool are dominated by harvesting and insect-induced mortality while atmospheric releases are primarily associated with fire (Apps et al. 1992)

Sensitivity Analyses with the CBM-CFS1

The CBM-CFS1 is restricted to a single time step and is driven by data generally pertaining to the reference year. Nevertheless the model may be used in a sensitivity analysis mode to explore the dependence of the national carbon budget on various factors, data and assumptions. A number of such analyses were performed (Kurz et al. 1992). The influences of changes in 1) disturbance regime and 2) biomass productivity are discussed here because both these factors are expected to change in a changing climate (Flannigan and van Wagner 1990, Zoltai et al. 1991).

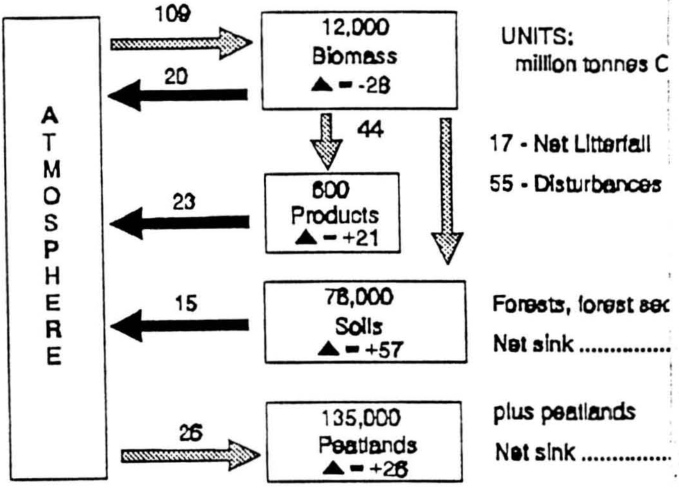

Fig. 4. Summary of carbon budget for Canadian forests and forest secto reference year 1986. (Adapted from Apps and Kurz 1991).

Table 4. Summary of the carbon budget of Canadian forests and forest s the reference year 1986 (in MtC).

Forest biomass	
Net growth prior to disturbance	92.0
Disturbance releases to atmosphere	–20.3
Disturbance transfer to soil	–55.4
Transfer to forest products	–44.2
Net change	–27.9
Forest soils	
Net detrital inputs prior to disturbance	17.3
Disturbance transfer from biomass	55.4
Disturbance releases to atmosphere	–15.2
Net change	57.4
Forest products	
Transfer from biomass	44.2
Releases to atmosphere	–23.1
Net change	21.1
Peatlands	
Net accumulation	26.2
Total (Net sink)	76.8

Table 7 shows a comparison of the two sensitivity runs with the standard run described in the previous section. The sensitivity run labelled 'Hi-Fire' was generated by increasing the standard run fire rate by a factor of 3 but leaving all other simulation conditions unchanged (i.e., as for the standard run). Although the resulting disturbance of 7.5 Mha is comparable to the actual area disturbed by fire in 1989, no attempt was made to replicate the geographical distribution of the 1989 disturbances. Under such highly disturbed conditions, the net sink drops from 77 MtC to 11 MtC and the net sink is only achieved by assuming that the peatland uptake of 26 MtC is maintained.

Can such increasing disturbance regimes be expected in a changing climate? Evidently they are very possible even under current conditions (Fig. 3) and increases have been predicted in a warming climate (Flannigan and van Wagner 1990). While this sensitivity result emphasizes the importance of predicting changes in the disturbance regimes, the analyses simulate only a one-year time step and do not include the delayed ecosystem responses.

The second sensitivity analysis (labelled 'Hi-Biomass' in Table 7) was performed to provide a rough sense of the importance of potential changes in biomass productivity. All biomass data in the CBM-CFS1 were arbitrarily increased by 10%. As for the Hi-Fire

Table 5. Percentage changes in carbon pools during the reference year 1986.

Pool	%
Forest Products	+3.75
Biomass	–0.23
Soils	+0.075
Peatland	+0.02

Table 6. Areas disturbed in reference year 1986 for each of five disturbance types, and disturbance-related C transfer from biomass to soil, biomass to atmosphere, and soil to atmosphere.

Disturbance	Area (10^3 ha)	Biomass to soil (MtC)	Biomass to Atmos. (MtC)	Soil to Atmos. (MtC)
Wildfire	2,496	21.0	18.6	14.3
Insect-induced mortality	388	12.4	0.1	0.0
Clearcut	775	19.9	0.0 [a)]	0.0 [a)]
Clearcut and slashburn	58	1.2	1.5	0.9
Partial cut	89	0.9	0.0 [a)]	0.0 [a)]

[a)] Zero because, at the time of cutting, C is not released directly to the atmosphere but is transferred to soil and detritus C pools from where it will be released through decomposition.

Table 7. The results of two sensitivity analyses experiments expressed change from the standard run (Table 4). The 'Hi-Fire' experiment was factor of 3 increase in fire-disturbed area. The 'Hi-Biomass' experiment wa all biomass values increased by a factor of 1.10. For both experiments Forest Product Sector and Peatland budgets were not explicitly simulate

	% change from standard rur	
	'Hi-Fire'	'Hi-Biomass'
Forest Biomass		
Net growth prior to disturbance	0.0	+10.0
Disturbance releases to atmosphere	+184.0	+9.6
Disturbance transfer to soil	+75.7	+10.6
Transfer to forest products	0.0	0.0
Net change	+284.5	−5.0
Forest Soils		
Net detrital inputs prior Disturbance	0.0	+10.0
Disturbance transfer from biomass	+75.7	+10.6
Disturbance releases to atmosphere	+188.2	+2.2
Net change	+23.1	+12.6
Total (Net Sink)	−85.9	+11.3

simulation, no attempt was made to partition biomass increases acros although it is fully recognised that any changes in forest productivity number of biogeochemical and climatic factors (Zoltai et al. 1991).

This Hi-Biomass sensitivity analysis yielded no surprises: as expected, biomass uptake both increased by the same 10%. Disturbance release the atmosphere increased by 9.6% , but transfers to the soil increase overall result was a slight increase in the net sink (11.3%) with the lar occurring in the soil pools (12.6%).

It would appear from these results that changes in both disturbance reg productivity play important, and perhaps compensating, roles in de carbon budgets. For such future-scenario assessments, it will be imp rate both the immediate and delayed ecosystem response to disturb sensitivity analysis (in which both disturbance regime and productivi ously varied) has been undertaken with a dynamic version of the C reported elsewhere (Kurz and Apps 1992b).

Discussion and Conclusions

The CBM-CFS is, we believe, the first comprehensive attempt to mc fluxes for forest ecosystems and forest sector activities at a national s obtained for the reference year 1986 reinforce the view that such an integrated approach is required in order to evaluate the forest sector's influence on global atmospheric carbon levels. Focussing on only one component or process (e.g., biomass growth or release of carbon by wildfire), or focussing too strongly on the pool sizes alone (e.g., soils), can give very misleading results.

For Canadian forests, the most dynamic carbon pools are associated with forest biomass, forest floor (detrital material), peat deposits, and wood stored in forest products. Although the pool sizes associated with each of these compartments differs by several orders of magnitude, they were found to make similar contributions to the reference year carbon budget. In the CBM-CFS, the net annual carbon exchange with the atmosphere is inferred from the net changes in the major compartments and these changes are driven by ecosystem processes, which transfer carbon between the compartments as well as with the atmosphere, having both immediate and delayed carbon budget implications.

The CBM-CFS1 results strongly indicate the importance of both growth-decomposition processes and natural disturbances (particularly wildfire) on annual carbon dynamics of Canadian forests. These two classes of processes have very different spatial and temporal characteristics. Spatially, the interaction of these processes over long timescales is assumed to be reflected in the forest distribution and structure across the landscape. In the CBM-CFS, this spatial variation is captured using an ecologically-based spatial representation. The CBM-CFS1 results indicate significant differences in annual carbon dynamics of the different spatial units. These differences arise from variations in forest spatial structure (spatial representation), forest age-class structure (largely determined by disturbance history) and forest function (growth and decomposition processes). This reflects, we believe, the medium- and long-term influence of both classes of processes on contemporary carbon dynamics (e.g., annual carbon budget), which must be taken into account when integrating across the landscape.

The CBM-CFS1 was, by design, data-hungry. As expected, a number of data gaps were exposed in the assembly of data for the CBM-CFS1. Where necessary, professional judgement of domain sector experts was used to assign process rate parameters, particulary for the forest product sector module and to a lesser extent, for the soil pool decomposition rates. Unfortunately, no data are immediately available to verify either the forest product or soil pool carbon estimates. With respect to soils, the CBM-CFS1 estimates are based on, and therefore very compatible with, the ORNL global data set. As mentioned earlier, an independent data set is currently being assembled for Canadian forest soils and, when completed, comparison with the CBM-CFS1 results should provide some degree of verification.

In comparison to the other model components, fewer data gaps exist for the biomass module of the CBM-CFS1. A notable exception is the lack of belowground biomass dynamics in the phase 1 estimates, but approaches to rectifying this deficiency are already underway. A less significant data gap exists for land areas for which there are no biomass data recorded in the biomass inventory. These areas are assumed to be carbon neutral (i.e., no changes in any of the associated carbon pools) with respect to the CBM-CFS1 annual budget as they are mainly associated with areas of low primary productivity. Treating these areas as carbon neutral likely has little affect on the budget (changes and fluxes) for the reference year but may result in a l the ecosystem carbon pools. This underestimation is likely to be most sig pools because the few available data indicate high soil C densities in n the forests where biomass data are missing. The biomass C pools size a to suffer similar underestimation problems because low biomass C densitie and low-productivity forests are the main reason why there are no bioma

Both basic inventory data and knowledge of dynamic processes are seri the landscape level for peatlands and, as a result, the CBM-CFS1 treats carbon pools in an unsatisfying way. The estimates of the CBM-CFS1 a best available data and knowledge (published and expert judgement) a as good an estimate as any currently available. The analytical structu inadequate for the analysis of future scenarios for at least two reasons. tal problem is that the two inventories defining the spatial distribution of f and of wetlands are not cross referenced; there is an unknown degree o between the two data bases. The second problem arises from the abse oriented models of peat dynamics that are applicable at national scales sentation of process controls on the productivity, the forms and rates of and the spatial distribution are lacking and this will severely limit any atte future-scenario changes in the peatland contribution to the landscape c

The CBM-CFS1, despite its data limitations, does indicate that Canadiar forest sector were a weak net sink of atmospheric carbon during the refe net sink was found to be unstable with respect to changes in disturban we therefore caution against extrapolating the reference year result Because of the uncertainties in the assessment, we are also relucta strong statements about the size of the sink relative to the missing car lated by Tans et al. (1990). We do note, however, that our result is of the order of magnitude (though smaller) as that required by Tans et al. comparisons with other modelled results, together with our sensitivity ever, give us cautious confidence in the sign and the order of magnitude

We believe that the net sink largely results from the age class distributio forest. This age-class distribution is reflected in the ecosystem dynan exchanges - both in the biomass and in the forest floor detrital pools distribution is an expression of the disturbance history at the lands includes both direct anthropogenic affects (e.g., harvesting as a di indirect anthropogenic influences on disturbance regimes (e.g., forest p ures). If there have been increases in forest productivity over the past would be inherently reflected in the biomass inventory and could accou simulated sink term. By the same argument, however, if decreases in fc have occurred these, too, would affect the size of the simulated sink tern earlier, such signals are probably not discernible in the inventory da made no attempt to do so.

In addition to estimating contemporary atmospheric carbon exchanges, simulation results exhibit significant carbon transfers between terrestri associated with disturbance processes. Although the CBM-CFS1 integration simulates only a single year time step, these transfers have implications for subsequent-year atmospheric carbon exchanges, particularly if the disturbance regimes (frequency, spatial distribution and intensity) change in the future. The explicit representation of disturbance processes in the CBM-CFS structure will facilitate the examination of these feedback effects over the 100 year time frame of interest (Kurz and Apps 1992b).

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References

Apps, M.J., W.A. Kurz and D.T. Price 1992. Estimating carbon budgets of Canadian forest ecosystems using a national scale model. In: Proceedings of Workshop "Carbon Cycling in Boreal Forests and Sub-Arctic Ecosystems: Biospheric Responses and Feedbacks to Global Climate Change", Ed. T. Kolchugina and T. Vinson, 9–12 September 1991, Oregon State University, Corvallis Oregon, 241–250.

Apps, M.J. and W.A. Kurz 1991. Assessing the role of Canadian forests and forest sector activities in the global carbon balance. World Res. Rev. 3(4), 333–344.

Bonnor, G.M. 1985. Inventory of forest biomass in Canada. Dep. Agr., Can. For. Serv., Ottawa, Ontario, 63p.

Bonnor, G.M. 1982. Canada's Forest Inventory 1981. Dep. Environ., Can. For. Serv., For. Statistics and Systems Br., Ottawa, Ontario.

Botkin, D.B., and L.G. Simpson 1990. Biomass of the North American Boreal Forest. Biogeochem. 9, 161–174.

Bray, J.R. and E. Gorham 1964. Litter production in forests of the world. Adv. Ecol. Res. 2: 101–157.

Broecker, W.S. and T.-H. Peng 1992. Interhemispheric transport of carbon dioxide by ocean circulation. Nature 356: 587–589.

Clymo, R.S. 1984. The limits to peat bog growth. Phil. Trans.Roy. Soc. Lond. B: 605–654

Ecoregions Working Group 1989. Ecoclimatic Regions of Canada, First approximation. Ecoregions of Canada Working Group of the Canada Committee on Ecological Land Classification. Ecological Land Classification Series No. 23, Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, Environment Canada, Ottawa, Ontario, 19 p., and map at 1:7,500,000.

Edmonds, R.L. 1984. Long-term decomposition and nutrient dynamics in pacific silver fir needles in western Washington. Can. J. For. Res. 10: 327–337.

Emanuel, W.R., G.C. Killough, W.M. Post, and H.H. Shugart 1984. Modelling t tems in the global carbon cycle with shifts in carbon storage capacity by Ecology 65: 970–983.

Forestry Canada 1988. Canada's forest inventory 1986. Canadian government Hull, Quebec, Canada, 60p.

Flannigan, M.D. and C.E. van Wagner 1990. Climatic change and wildfire in Car Res. 21: 66–72.

Gessel, S.P. and J. Turner 1976. Litter production in western Washington D Forestry 49: 63–72.

Gorham, E. 1988. Canada's peatlands: their importance for the global carbon c effects of "greenhouse" climatic warming. Trans. Roy. Soc. of Can. V, 3: 21–

Gorham, E. 1991. Northern peatlands role in the carbon cycle and probable res warming. Ecological Applications 1(2): 182–195.

Gray, S.L., and K. Nietmann 1986. Canada's forest inventory 1986 – techr Information report PI-X-86. Petawawa National Forestry Institute, Forestry C

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattir S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack Jr., ar 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin 1990. Effects on carbon storag old-growth forests to young forests. Science 247: 699–702.

Hogg, E.H., V.J. Lieffers, and R.W. Wein 1992. Potential carbon losses from pe of temperature, drought cycles, and fire. Ecological Applications 2(3): 298–3

Holling, C.S. 1992. Forest insects and the boreal landscape. In: A systems Ana Boreal Forest., ed. H.H. Shugart, R. Leemans and G.B. Bonan, Cambridge Cambridge, 565 p.

Holling, C.S. 1992b. Cross-scale morphology, geometry and dynamics of ecc Mon., in press.

Honer, T.G., W.R. Clark, and S.L. Gray 1991. Determining Canada's Fores Volume Balance, 1977–1986. In: Inf. Rep. PI-X-101: Canada's Timber Re Brand, Petawawa National Forestry Institute, Proc. of national Conference, V 2–5, 1990, 17–25.

Honer, T.G., and A. Bickerstaff 1985. Canada's forest area and wood volume ba an appraisal of change under current levels of management, Can. For. Cent., Victoria, British Columbia, Inf. Rep. BC-X-272, 84 p.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Woodwell 1983. Changes in the carbon content of terrestrial biota and soils 1980: A net release of CO_2 to the atmosphere. Ecol. Monographs 53(3), 23

Kauppi, P.E., K. Mielikäinen, K. Kuusela 1992. Biomass and carbon budget of 1971 to 1990. Science 256: 70–74.

Kimmins, J.P. 1985. Future shock in forest yield forecasting: the need for a n Chron. 61(6): 503–512.

Kivinen, E. and P. Pakarinen 1981. Geographical distribution of peat res peatland complex types in the world. Annales Academiae Scientiarium Fen 28.

Kurz, W.A., M.J., Apps, P.J. McNamee,and T.M. Webb 1991. The contribution to the carbon budget of the Canadian forest sector: a conceptual model. Burning: atmospheric, climatic and biospheric implications (Ed. J.S. Levin

Cambridge, Mass., 339–344.

Kurz, W.A. and M.J. Apps 1992a. Atmospheric carbon and Pacific Northwest forests, In: Wall, G. (ed.). Department of Geography Publication Series, Occasional Paper, University of Waterloo, 69–80.

Kurz, W.A. and M.J. Apps 1992b. The carbon budget of Canadian forests: A sensitivity analysis of changes in disturbance regimes, growth rates, and decomposition rates. Environ. Pollution. In press.

Kurz, W.A. and M.J. Apps 1992c. Estimation of root biomass and dynamics for the carbon budget of the Canadian forest sector. In preparation.

Kurz, W.A. , M.J Apps, T.M. Webb, and P.J. MacNamee 1992. The carbon budget of the Canadian forest sector: phase 1. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta, Inf. Rep. NOR-X-326. 93 p.

Kuusela, K. 1990. The dynamics of boreal coniferous forests. Finnish National Fund for Research and Development , Sitra, Helsinki, 172 p.

Lowe, J.J. 1991. Canada's forest inventory: The sustainable commercial harvest base and its growth rate. In Information Report PI-X-101: Canada's Timber Resources, Ed. D.G. Brand, Petawawa National Forestry Institute, Proc. of national Conference, Victoria, B.C., June 2–5, 1990, 33–36.

Maini, J.S. 1990. Sustainable development of the Canadian forest sector. For. Chron. 66(4): 346–349.

McClaugherty, C.A., J.D. Aber, and J.M. Melillo 1984. Decomposition dynamics of fine roots in orested ecosystems. Oikos 42: 378–386.

oore, T.R. 1989. Plant production, decomposition and carbon efflux in a subarctic patterned fen. rctic Alp. Res. 21: 156–162.

oore, P.D. and D.J. Bellamy 1974. Peatlands. Springer-Verlag New York Inc., 221 p.

National Wetlands Working Group 1986. Wetland distribution in Canada. In Canada's Wetlands, Mapfolio. Energy Mines and Resources and Environment Canada, Ottawa, Ontario.

Overpeck, J.T., D. Rind, and R. Goldberg 1990. Climate-induced changes in forest disturbance and vegetation. Nature 343: 51–53.

Piene, H. and K. Van Cleve 1978. Weight loss of litter and cellulose bags in a thinned white spruce forest in interior Alaska. Can. J. For. Res. 8: 42–46.

Rizzo, B. and E. Wiken 1992. Assessing the sensitivity of Canada's ecosystems to climatic change, Climate Change 21: 37–55.

Rowe, J.S. 1972. Forest Regions of Canada. Can. Dep.Fish. Environ., Can. For. Serv., Ottawa, Ontario, Publ. No. 1300.

Sarmiento, J.L. and E.T. Sundquist 1992. Revised budget for the oceanic uptake of anthropogenic carbon dioxide. Nature 356: 589–593.

Schlesinger, W.H. 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. Nature 348: 232–234.

Shugart, H.H., and D.C. West 1980. Forest succession models. Bioscience 30(5), 308–313.

Shuttleworth, W. J. 1991. The Modellion concept. Reviews of Geophysics 29(4), 585–606.

Tans, P.P., I.Y. Fung, and T. Takahashi 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247: 1431–1438.

Van Wagner, C.E. 1988. The historical pattern of annual burned area in Canada. For. Chron. 64: 182–185.

Vogt, K.A., C.C. Grier, and D.J. Vogt 1986. Production, turnover and nutrient dynamics of above and belowground detritus of world forests. Adv. Ecol. Res. 15: 303–377.

Woodwell, G.M. and K. Ramakrishna 1989, Guest Editorial: The warming of the earth: perspectives and solutions in the third world. Environ. Conserv. 16(4): 289–291.

Zinke, P.J., A.G. Strangenberger, W.M. Post, W.R. Emanual, and J.S. Olsen Organic Soil Carbon and Nitrogen Data. CDIC Numeric Data Collectior Information Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Zoltai, S., T. Singh, and M.J. Apps 1991. Aspen in a changing climate. In: S. Chapman, editors. Aspen management for the 21st century. Proceedings of November 20–21, 1990, Edmonton, Alberta. For. Can., Northwest Reg., No Poplar Counc. Can., Edmonton, Alberta, 143–152.

Zoltai, S.C. 1989. Ecoclimatic Provinces of Canada and man-induced climatic c on Ecol. Land Clas. Newsletter Number 17.

Zoltai, S.C., and D.H. Vitt 1990. Holocene climatic change and the distributi western interior Canada. Quatenary Research 33: 231–240.

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CARBON BALANCE OF WORLD'S FORESTED ECOSYSTEMS: TOWARDS A GLOBAL ASSESSMENT

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in Joensuu, Finland, 11–15 May 1992

Painatuskeskus oy Helsinki