Ecological Applications, 9(2), 1999, pp. 526–547

A 70-YEAR RETROSPECTIVE ANALYSIS OF CARBON FLUXES IN THE CANADIAN FOREST SECTOR

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Abstract. The Carbon Budget Model of the Canadian Forest Sector (CBM–CFS2) is a framework for the dynamic accounting of carbon pools and fluxes in Canada's forest ecosystems and the forest product sector. The model structure, assumptions, and supporting databases are described. The model has been applied to estimate net ecosystem carbon fluxes for Canada's 404 Mha forest area for the period 1920–1989. Changes in disturbance regimes have affected the forest age class structure and increased the average forest age during the period 1920–1979. The resulting changes in dead organic matter and biomass carbon during this period were estimated with the model. In the last decade of the analysis, large increases in disturbances, primarily fire and insect damage, have resulted in a reduction in ecosystem carbon storage. The estimates of biomass pool sizes obtained are consistent with those of other studies, while dead organic matter carbon pool estimates remain somewhat uncertain. Sensitivity analysis of several sources of uncertainty indicate that the pattern of net changes in ecosystem carbon pools over the 70-yr period was hardly affected and that the numerical estimates changed by <15%.

Key words: boreal forest; Canada; carbon; carbon budget model; CBM–CFS2; climate change; decomposition; disturbance; fire; harvesting; insects; soil.

INTRODUCTION

The predictions of the present and future carbon (C) dynamics of forest ecosystems require an analysis of the forest dynamics in the recent past. Factors such as forest age class structure, disturbance history, and woody debris, resulting from harvesting and natural disturbances, all contribute to the present and future C dynamics and must be quantified before projections of the future contributions of forest ecosystems to the global atmospheric C balance can be made.

Several recent studies have estimated national or regional forest sector C budgets (Harmon et al. 1990, Apps and Kurz 1991, Kauppi et al. 1992, Sedjo 1992, Dixon et al. 1994). Many of these concluded that temperate and boreal forests are C sinks, but the reasons offered for the C uptake differed among studies. Moreover, some studies found a forest sector C source (e.g., Harmon et al. 1990). Global budgets of C sources and sinks still contain a discrepancy between the estimates of C emissions and uptake (Tans et al. 1990). Thus, the possible role of terrestrial ecosystems in the global C budget continues to be debated (Ciais et al. 1995, Houghton 1996).

The objective of this study was to analyze the change in ecosystem C storage in Canada's forest ecosystems over the 70-yr period 1920–1989. The analysis employs a detailed C accounting framework that makes extensive use of national forest inventory information, long-term records of forest disturbances, and simulation modeling. This work builds on an earlier static version of the carbon budget model of the Canadian forest sector (CBM–CFS1) that estimated C pools and fluxes for a single year (Apps and Kurz 1991, Kurz et al. 1992). The details of the model structure, underlying assumptions, and databases employed in the 70-yr analysis are described. Several sources of uncertainty in the model results are analyzed and discussed.

METHODS: MODEL DESCRIPTION

Forest dynamics in Canada are strongly influenced by stand-replacing disturbances, such as wildfire and forest insects. A national-scale C budget must, therefore, capture both C dynamics associated with growth and decomposition in forest stands and population dynamics of the stands. Indicators of C dynamics at the stand level are the C content of biomass and soil C pools, growth and decomposition rates, and C transfers between biomass and soil pools. Indicators of population dynamics of stands are age class distribution of stands and areas annually disturbed. A national-scale C budget also requires definition of initial conditions of the system and integration of the relevant indicators of C pools and fluxes over space and time. Each of these will be described in more detail.

CBM–CFS2 (Version 2) is a general framework for the dynamic accounting of C pools and fluxes in terrestrial ecosystems. The analysis area (e.g., a country or a forest management unit) is divided into separate

Manuscript received 19 November 1997; revised 11 June 1998; accepted 12 June 1998; final version received 6 July 1998.
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spatial entities (e.g., ecological or climatic regions). The model has been used for forest areas as large as Canada (404 Mha; Kurz et al. 1995) and as small as the Foothills Model Forest in Alberta (0.8 Mha; Price et al. 1996, Price et al. 1997). To analyze the C dynamics of an individual stand, however, other more sophisticated ecosystem models may be more appropriate (e.g., Mohren and Klein Goldewijk 1990, Cropper and Gholz 1993). Stand level models alone, however, do not capture the landscape level dynamics, which have recently been shown to be of importance to the Canadian forest sector C budget (Kurz et al. 1995, Kurz and Apps 1996).

The CBM–CFS2 consists of a large database that contains information on ecosystem types, their area, and C contents; a second database of historic disturbance statistics for the period 1920–1989; several other input data files defining stand level disturbance impacts, climatic conditions, and stand growth dynamics; and the computer model that performs the simulations and analyses. Information on ecosystem C contained in biomass and dead organic matter C pools is stored >12 000 records, each characterizing a specific forest ecosystem type, age, and area combination. The model simulates the changes in ecosystem pools, and the associated C fluxes, from an initial condition in 1920–1989. It simulates forest growth and decomposition, the area annually disturbed by natural and anthropogenic disturbances, and the planting and regrowth of forests after disturbances. The model generates detailed output files and summary information for each spatial unit, ecoclimatic province, and for all of Canada.

Biomass C harvested annually is transferred to the forest product sector where it is converted to various products with specific use patterns and C retention characteristics (Kurz et al. 1992). Because the focus of the present study is on changes in the C storage in Canadian forest ecosystems, a description of the forest product model will not be given here. An earlier version of the forest product model has been previously described (Kurz et al. 1992).

National stratification of forest ecosystem types

The National Forest Biomass Inventory (NFBI) (Bonnor 1985) is the primary source for three sets of information used in the CBM–CFS2. First, the inventory was used to stratify all of Canada's forest area into ecosystem types and to determine the area in each type. Second, for each ecosystem type, a growth curve describing aboveground biomass dynamics was developed from the inventory data. Third, the forest age class structure compiled for the inventory was used in the reconstruction of the age class structure in 1920, which was the start year of the model simulation. Note that biomass data in the inventory are not used as input to the model. They are, however, used in the comparison of the simulated and inventoried biomass.

The NFBI contains about 50 000 grid cells of variable size (Bonnor 1985). For present purposes, the inventory information was aggregated to 42 spatial units that were derived from the overlay of the administrative boundaries of Canada's provinces and territories with those of the ecoclimatic provinces (Ecoregions Working Group 1989; see Kurz et al. 1992, Apps and Kurz 1994).

TABLE 1. Forest area (Mha) in the inventory for Canada for 11 ecoclimatic provinces.

Ecoclimatic province	Forest area (Mha)
Boreal West	97.6
Boreal East	120.2
Subarctic	85.2
Cool Temperate	25.8
Moderate Temperate	0.2
Grassland	2.6
Cordilleran	47.3
Interior Cordilleran	14.6
Pacific Cordilleran	9.1
Subarctic Cordilleran	0.9
Arctic	0.6
All of Canada	404.2

A summary of forest area by ecoclimatic province is included in Table 1. The total forest area in the database derived from the NFBI is 440.8 Mha. Biomass data are available for 404.2 Mha. The remaining 36.6 Mha, which are primarily nonproductive areas in northern regions or at high elevations, are not considered in this analysis. The most recent Canadian Forest Inventory (CanFI) (Lowe et al. 1996) reports a forest area of 417.6 Mha, which suggests that the earlier estimate of 440.8 Mha may have included some nonforested area.

Within each of the 42 spatial units, the forest area is further stratified by productivity (3 classes), site quality (8 classes), stocking (3 classes), maturity class (6 classes), and forest type (softwood, mixed wood, hardwood) (for definitions see Bonnor 1985). The combination of 42 spatial units and the other 5 stratifiers yields 457 distinct forest ecosystem types. The total area associated with each ecosystem type is derived from the inventory information, but the information on the geographic distribution of the area within the 42 spatial units is not retained in the model database.

Biomass growth and mortality

The CBM–CFS2 uses growth curves to describe the dynamics of two species groups in each ecosystem type. At present, these are defined as a softwood and a hardwood species group, but the model can also accommodate other definitions, e.g., two softwood species.

For each species group, the inventory contains information on four aboveground biomass pools: (1) stemwood and bark of trees of merchantable size, (2) foliage of trees of merchantable size, (3) other components of trees of merchantable size, and (4) total aboveground biomass of trees of submerchantable size.

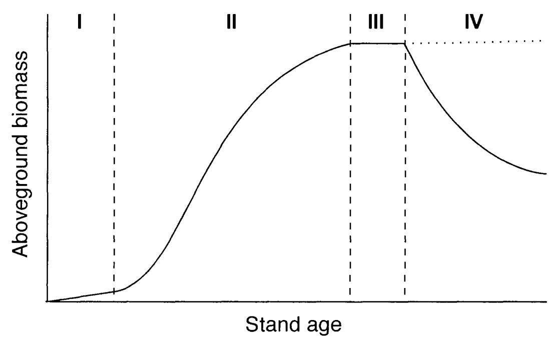

FIG. 1. Summary of the four growth phases in the CBM–CFS2. See Table 2 for the equations that are used to simulate aboveground biomass dynamics in the CBM–CFS2.

Merchantability criteria are based on species and diameter and are defined by administrative province (Gray and Nietman 1989). Other biomass components such as shrubs, herbs, or mosses are not included in the NFBI. The average biomass values for the softwood and hardwood species groups, for each maturity class of each ecosystem type, are compiled from the NFBI.

The average age of each maturity class in the NFBI is calculated using the age class definitions for maturity classes in each province and forest region (Rowe 1972) from CanFI 1986 (Forestry Canada 1988). The biomass–age data pairs for each ecosystem type are then used in the calculation of the growth curves.

Growth dynamics for the aboveground biomass of each species group are defined for each of the 457 ecosystem types. Growth dynamics are described by a growth model that distinguishes four phases of stand development: (1) regeneration, (2) immature growth phase, (3) mature growth phase, and (4) an overmature growth phase (Fig. 1 and Table 2; Kurz and Apps 1994). For each growth model, the parameters for each growth phase, and the rules for the transitions between growth phases, are derived from the NFBI.

During the regeneration phase (nominally 10 yr), only small linear increases in biomass C are simulated (Fig. 1 and Table 2). During the immature growth phase, a logistic growth model describes C accumulation. Parameters defining the immature phase duration and biomass C accumulation are derived from the biomass–age data pairs compiled from the NFBI. A linear model describes biomass dynamics during the mature phase, although its parameters are currently chosen to represent constant biomass for a 10-yr period. During the overmature phase, data in the NFBI are used to determine whether biomass is constant, or whether stand breakup occurs.

The parameters for the immature phase of the growth model are estimated using a two-step procedure. For each growth model, initial parameters are determined from the area-weighted average biomass in each maturity class in the NFBI. The highest biomass value in the inventory represents the average biomass of the stands within a maturity class, however, and not the carrying capacity defined by the logistic growth function. Direct application of logistic growth functions to estimate regional biomass thus yields systematical underestimation of biomass, which is a bias observed in

TABLE 2. (A) Equations that are used to simulate aboveground biomass dynamics in the CBM–CFS2. See Fig. 1 for graphical depiction of the four growth phases in the CBM–CFS2. (B) Definitions of parameters.

Phase or definition	Equation	Transition
A) Equations		
I. Regeneration phase	$B_t = B_{\mathrm{init}} + a \times t$	Transition to II after n years
II. Immature growth phase	$B_t = B_{t-1} + B_{t-1} \times r\left(1 - \frac{B_{t-1}}{B_{\max}}\right)$	Transition to III when $B_t = q \times B_{\max}$
III. Mature growth phase	$B_t = B_{\mathrm{imm}} + c \times t$	Transition to IV after m years
IV. Overmature growth phase		
No decline (e.g., even-aged stands)	$B_t = B_{\mathrm{mat}}$	No transition
Decline	$B_t = B_{\mathrm{mat}}(1 - d)^t$	Transition to II when $B_t = q \times B_{\mathrm{mat}}$

B) Parameters

t = Number of years in current state.
B_{init} = Initial biomass density (typically = 0).
B_{reg} = Biomass at end of regeneration phase ($B_{\mathrm{reg}} > 0$).
B_{imm} = Biomass at end of immature growth phase.
B_{mat} = Biomass at end of mature growth phase.
n = Duration of regeneration phase (default = 10 yr).
m = Duration of mature growth phase (default = 10 yr).
c = Growth rate during mature growth phase (default = 0).
d = Rate of biomass decline during overmature growth phase (defined from inventory data or default = 1% mass/yr for softwood, 2% mass/yr for hardwood).
p = Proportion of maximum biomass at which growth resumes (default = 0.2).
a, r, q, $B_{\max}$ = Parameters obtained by fitting to inventory data.

previous assessments using the static CBM–CFS1 (Apps and Kurz 1991, Kurz et al. 1992).

A second step was performed to remove the bias. For each ecosystem type, the logistic growth model was iteratively scaled, such that the total biomass predicted by the growth model equaled the total biomass of that ecosystem type in the inventory. The former is the sum of products of the biomass (Mg C/ha) in each age class (predicted by the growth model) and the area (ha) in each age class. The total biomass in each ecosystem type was calculated from the inventory data as the sum of products of the average biomass (Mg C/ha) in each maturity class multiplied by the area in the maturity class. Iterative adjustments of the carrying capacity in the logistic equation were performed until growth model biomass estimates were within $\pm 1\%$ of the inventory estimate.

The data in the NFBI indicate that overmature stands often have less biomass than mature stands of the same type. The exponential parameter for the overmature decline phase is calculated from the inventory data, such that biomass declines from the value at the end of the mature phase to the biomass value in the overmature phase. If no data exist to define the biomass in the overmature maturity class, the rate of biomass decline defaults to 1% mass/yr for softwood and 2% mass/yr for hardwood species. For uneven-aged stands ($<1\%$ of the area in the inventory) biomass is assumed not to decline in the overmature growth phase.

The CBM–CFS2 represents disturbances of forest stands by harvesting, fire, and insects, but the disturbance interval for individual stands is not known a priori. Because individual stands are stochastically selected for disturbance, some forest area could escape disturbance for prolonged periods of time in the overmature state. The emergence of regeneration in such stands is assumed to occur when the biomass drops to 20% of the mature phase biomass. At this point the dynamics revert to the immature growth phase, and thus resume growth. The reduction in competition associated with the opening of the overstorey canopy during this breakup is assumed to permit understorey trees to increase in biomass and to accumulate C.

Each growth curve describes the biomass dynamics of total aboveground tree biomass for the softwood or hardwood species group. Linear regression models are used to separately predict the proportion of each of the four aboveground biomass components, as a function of total biomass for softwood and hardwood species, in every spatial unit. The parameters (slope and intercept) for the 336 (2 species groups $\times$ 4 biomass components $\times$ 42 spatial units) regression equations are derived from the NFBI.

For each of the two species groups, two belowground biomass pools are used to represent coarse and fine root biomass. Estimates for these pools are derived using regression equations that predict root biomass as a function of aboveground biomass for each the softwood and hardwood species group (Kurz et al. 1996). Additional equations predict the proportion of fine root biomass as a function of total belowground biomass, as well as predicting fine root production as a proportion of fine root biomass (Kurz et al. 1996).

All biomass data were converted to C values by assigning the specific C content to each biomass component. By default, all biomass components are assigned a C content of 0.5 g C/g ovendry biomass.

Biomass to dead organic matter transfers

Biomass is transferred to dead organic matter (DOM) C pools (which in the model represent litter, coarse woody debris, and soil organic matter, except peat). These transfers are simulated as three distinct processes: litterfall, mortality associated with stand breakup, and disturbances.

Litterfall includes all annual transfers of biomass to the DOM C pools, such as foliage and fine root turnover, and annual losses from the other biomass pools. Table 3 summarizes the parameter values for each biomass pool of the softwood and hardwood species group in each ecoclimatic province that are used to simulate the litterfall component of annual biomass to DOM transfers. The annual transfer of fine root biomass is estimated as 82% and 65–95% of standing fine root biomass in the softwood and hardwood species groups, respectively (Kurz et al. 1996).

Mortality associated with stand breakup in the overmature growth phase accounts for an additional annual transfer to the DOM C pools. The amount transferred is derived in the model by comparing the size of biomass pools at the beginning and end of a simulation time step.

Disturbances such as wildfire or logging alter the distribution of C in the forest ecosystem. At the time of disturbance, the model simulates transfers between ecosystem C pools, and from biomass and DOM C pools to the atmosphere (in the case of wildfire) and to the forest product sector (in the case of harvesting) (see *Methods: Disturbances*).

Dead organic matter dynamics

The CBM–CFS2 represents DOM in four "soil" C pools (designated as very fast, fast, medium, and slow pool), characterized by the type of biomass input and C turnover rates (Fig. 2). Separate DOM pools are maintained for each record in the model database. From the three DOM detritus pools, C is released to the atmosphere, transferred to the slow DOM C pool representing humified organic matter, or leached into aquatic systems. Although transfers to aquatic systems may play a role in the C fluxes of forest ecosystems, no national-scale statistics are available to parameterize these transfers in the model. It is therefore assumed that all losses from DOM C pools are released directly to the atmosphere (Fig. 2).

Decomposition rates for DOM C pools are calculated

TABLE 3. Parameter values (percent of standing biomass) for the simulation of the litterfall component of annual biomass to DOM transfers for different biomass pools and ecoclimatic provinces.

	Litterfall component (% mass/yr)				
	Foliage				
Ecoclimatic province	Softwood	Hardwood	Stemwood	Branches†	Coarse roots
Arctic	5	95	0.60	3	2
Subarctic	5	95	0.60	3	2
Boreal West	10	95	0.50	4	2
Boreal East	10	95	0.50	4	2
Cool Temperate	15	95	0.67	4	2
Moderate Temperate	15	95	0.77	4	2
Grasslands	15	95	0.60	4	2
Subarctic Cordilleran	10	95	0.60	4	2
Cordilleran	10	95	0.45	4	2
Interior Cordilleran	10	95	0.45	4	2
Pacific Cordilleran	15	95	0.60	4	2

† The branches biomass pool also includes biomass in the other submerchantable biomass pool.

by modifying base decomposition rates using the average (1951–1980) of the mean annual temperature (MAT) for each spatial unit. Decomposition rates, therefore, vary among spatial units as a function of MAT (Schimel et al. 1994), but temperatures do not change over time in the model simulations reported here.

Base decomposition rates at the reference mean annual temperature (RefTemp = 10°C) for the very fast, fast, medium, and slow DOM C pools are 0.5, 0.14, 0.037, and 0.0068/yr, respectively (Kurz et al. 1992). A temperature-dependent modifier (TempMod) of these rates is calculated based on a Q_{10} value of 2.0 and the mean annual temperature (MAT_i) of each spatial unit *i*:

$$\text{TempMod} = e^{((\text{MAT}_i - \text{RefTemp}) \times \ln(Q_{10}) \times 0.1)}. \quad (1)$$

The decomposition rates for all but the slow DOM C pool are further modified to reflect accelerated decomposition following disturbances (Binkley 1984). The model calculates an increase in decomposition rates following disturbances that remove aboveground biomass. As aboveground biomass accumulates, and the stand canopy closes, the accelerated decomposition slows down and approaches base decomposition rates. A reduction factor (*b*) is calculated such that at 10% of maximum biomass, decomposition rates are reduced by 50% ($b = -6.93$) of the difference between maximum and base decomposition rates. This factor is used to calculate a second modifier of decomposition rates (StandMod) that accounts for changes in stand canopy conditions:

$$\text{StandMod} = 1 + (\text{MaxDecayMult} - 1) \times e^{(b \times (\text{TotBio}_s / \text{MaxBio}_g))} \quad (2)$$

where TotBio_s is the total aboveground biomass (Mg C/ha) and MaxBio_g the maximum aboveground biomass for the growth curve *g* associated with stand record *s*, and MaxDecayMult is the open canopy decay rate multiplier (default value = 2). For the slow DOM C pool, StandMod = 1 always. Both the temperature modifier (Eq. 1) and the stand modifier (Eq. 2) are used to calculate the decomposition rate for each of the four DOM C pools:

$$\text{Decay}_j = \text{BaseDecay}_j \times \text{TempMod} \times \text{StandMod} \quad (3)$$

where Decay_j is the decomposition rate of the *j*th DOM C pool (very fast, fast, medium, and slow) and BaseDecay_j is the reference decomposition rate of that pool at 10°C MAT.

Data on DOM C content in forest ecosystems are not included in the national forest inventories. Initial val-

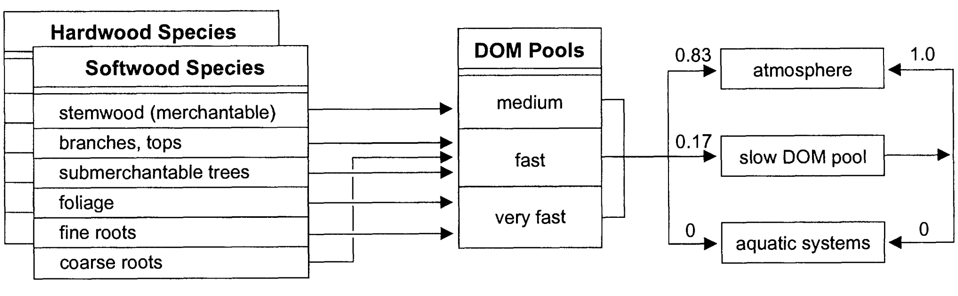

FIG. 2. Summary of 12 biomass and four DOM (dead organic matter) C pools contained in each record in the database. As litterfall, each biomass component is assigned to one receiving DOM pool.

ues for DOM C were derived from the Oak Ridge National Laboratories (ORNL) database on world organic C content (Zinke et al. 1986). The individual data records for the different ecosystem types were obtained from these initial spatial unit averages through simulations. Estimates of litter and coarse woody debris C, not in the ORNL database, were also obtained with these simulations.

The CBM–CFS2 does not presently simulate the dynamics of peat C. Estimates of peat pools and fluxes have not been updated from those reported earlier (Kurz et al. 1992).

Disturbances

For the purposes of simulating C dynamics, disturbances are regarded as events during which the distribution of C in the ecosystem is altered and after which the dynamics of ecosystem C pools are changed. Disturbances play a particularly important role in the population dynamics of Canadian forest stands because they are often stand replacing, i.e., following disturbance the existing stand is replaced with a regenerating stand. The CBM–CFS2 distinguishes seven types of disturbances: (1) wildfire, (2) insect-induced stand mortality, (3) clear-cut logging, (4) clear-cut logging with slash burning, (5) salvage logging following wildfire, (6) salvage logging following insect-induced stand mortality, and (7) partial cutting. Within each spatial unit, each disturbance type has a specific disturbance matrix (for examples see Kurz et al. 1992), which defines the proportion of each ecosystem C pool transferred to others, to the atmosphere, and to the forest product sector at the time of disturbance.

A set of rules for each disturbance type defines the criteria by which the model selects the area of various forest stands (individual records) to disturb at each time step. The main criteria are the following: harvesting is applied first to stands with the highest volume (up to an upper limit of 2% of the area in an eligible record per year); insect disturbances are applied to softwood stands in the mature and overmature growth phases; and fires can occur in all stands that have total biomass ≥1 Mg C/ha.

For each spatial unit and time step, the area to be disturbed by each of the seven disturbance types is specified in an input file to the model. Thus, both retrospective analyses (such as are reported here) that are based on historical data, and projective analyses (as in Kurz and Apps 1995) that are based on prescribed scenario data, can be performed.

Synthesis of pools and fluxes

At any point in time, the state of the C pools in the forest ecosystems is represented by the database records that are updated in each time step. Annual biomass dynamics are simulated with the growth module, annual DOM dynamics are simulated with the soils module, and, at each 5-yr time step, disturbances are applied to the appropriate records.

Each record in the database represents the area within the spatial unit that is of a specific ecosystem type and age. For the year 1920, the model represents Canadian forests as 12 339 records distributed amongst 457 ecosystem types, each partitioned into 27 age classes that range from 5 to >50 yr in width. During the simulation, the age of each undisturbed record increases. New records are added to represent newly disturbed areas. Increases in the number of records are limited by merging selected records after each 5-yr time step. In the simulations reported here, only records from the same growth type that have been created from disturbances in the current time step are eligible to be combined to form a new record. The new record combines the area of the merged records and assigns area-weighted average C content (Mg C/ha) to each biomass and soil C pool in the merged record.

At the end of each time step t, the total C storage (TC_t) in Canadian forests ecosystems is calculated by summing over all records representing the area and C pools in each ecosystem type and age range:

$$TC_t = \sum_{j=1}^{n} \mathrm{Area}_{j,t} \times (\mathrm{BioC}_{j,t} + \mathrm{SoilC}_{j,t}) \qquad (4)$$

where j indicates the record, $\mathrm{Area}_{j,t}$ is the area (ha) of record j at time t, and $\mathrm{BioC}_{j,t}$ and $\mathrm{SoilC}_{j,t}$ are, respectively, the biomass and DOM C contents (Mg C/ha) of record j at time t. Specific C pools, such as aboveground biomass C, are calculated similarly by summing the appropriate state variables of each record.

Flux estimates are obtained at each time step by summing appropriate variables. For example, the transfer of biomass C to the forest product sector is the sum of the transfers associated with harvesting. Disturbance releases of C from biomass pools to the atmosphere are the sum of the releases from all disturbance types that directly release C at the time of disturbance.

The Historic Disturbance Record

Overview

Data on the three major types of disturbances (fires, insects, and harvesting) and planting of disturbed areas, were compiled primarily from publications by the Canadian Forest Service, Statistics Canada, and provincial forestry. Where possible, national sources were used in order to facilitate comparisons over time between different regions. Provincial publications and annual reports were used to compile details of the spatial distribution of disturbances that are not reported in national statistics. Disturbance statistics for administrative regions within a province or territory were subsequently allocated to the appropriate ecoclimatic provinces (Ecoregions Working Group 1989) using a set of proportional multipliers derived from their observed areal distribution.

The disturbance statistics reported by different sources and in different time periods were not always fully compatible, due to differences in reporting, terminology, and in the methodology used to collect and interpret the data. To the extent possible, these discrepancies have been reconciled. See *Initial conditions: Age class structure* for a discussion of a validation analysis in which the area affected by stand-replacing disturbances in the past is compared with the recent forest age class structure.

Area harvested

Data on forest harvesting are typically recorded with considerable detail and spatial resolution. Harvesting statistics were compiled from annual reports of the British Columbia Ministry of Forests (BC Ministry of Forests 1926–1990), Ontario Ministry of Natural Resources (1973–1974), Statistics Canada (1976), Manitoba Natural Resources (1987, 1992), Canadian Forestry Service (1988), Heartwell (1988), Kuhnke (1989), Forestry Canada (1992); W. Blinn (*personal communication*), T. R. Isherwood (*personal communication*), and B. Lamont, (*personal communication*).

Clear-cut and partial-cut harvesting were reported in these statistics. Clear-cut logging with slash burning was added to the disturbance database using provincial statistics on slash burning. Slash burning, a process in which logging residues are deliberately burned to facilitate planting and regeneration, has been practiced primarily in Ontario and British Columbia. Two additional harvesting types, salvage logging of areas disturbed by fire or insects, were included because they result in modified C dynamics. The reported total area with clear-cut harvest was partitioned into four harvest types (i.e., clear-cut, clear-cut with slash burning, salvage logging following fire, and salvage logging following insect disturbance).

Statistics describing the area harvested (as distinct from volume removed) were available only back to ~1975 (this date varies with the region and data source). Harvested area estimates for earlier years were derived from harvested volume statistics, which are available back to 1922. For each province (or, where possible, for each administrative region within a province), the average volume-to-area harvested ratio was calculated from all available data. This ratio was then applied to the reported harvested volume to derive the estimates of total harvested area. These provincial estimates were then apportioned by harvest-type based on the average proportions calculated from all available data. Estimates for volume harvested in 1920 and 1921 were obtained by linearly extrapolating the 1922–1923 statistics.

Area salvage logged

In all provinces and territories, pest- and fire-killed stands are harvested if the timber is accessible and of acceptable quality. Statistics on harvests of such timber are usually implicitly incorporated in the provincial/territorial harvest totals reported by the publications listed previously. Thus, while salvage harvesting is common, specific data for salvage harvesting are not readily available. Double accounting (i.e., disturbing the same forestland first through fire or pest, and then through harvest) of disturbances was avoided.

To our knowledge, the only published estimates of area salvage logged in Canada are from Honer and Bickerstaff (1985), who estimated for each province and territory the proportion of the area pest killed or fire killed during 1977–1981 and subsequently salvage logged. Staff of the Canadian Forest Service in each province and territory was contacted, and an update or confirmation of the proportions used in Honer and Bickerstaff (1985) was requested. Table 4 lists the salvage proportion estimates based on the replies of that survey. The proportions from Honer and Bickerstaff (1985) are used in the table if an update could not be provided or if the contact considered the previous estimate adequate. In the absence of historical data, the proportions of salvaged areas (Table 4) are assumed to have remained constant for the period 1920–1989.

The area salvage logged annually was calculated as follows. First, the area affected by harvest and by insects and fire was calculated for each spatial unit and year. Second, in each spatial unit, the maximum area deemed available for salvage logging was estimated by applying the proportions in Table 4 to the area pest killed or fire killed each year. If the area available for salvage logging was greater than the maximum allowable proportion of the area harvested (defined in Table 4), the area salvage logged was reduced by first decreasing salvage logging in burned stands, and then in insect-killed stands, until the area constraints were met. Finally, the resulting estimates of area salvage logged

TABLE 4. Estimates of the maximum proportion of the pest-killed or fire-killed area that can be harvested in salvage logging operations in each province and territory, and the maximum proportion of the area harvested annually that can be conducted as salvage logging operations.

Province	Proportion of area salvage logged: Pest-killed stands	Proportion of area salvage logged: Fire-killed stands	Maximum proportion of annual harvest
Newfoundland	0.07	0.01	0.65
Nova Scotia	0.35	0.25	1.00
Prince Edward Island	0.75	0.90	1.00
New Brunswick	0.80	0.25	1.00
Quebec	0.20	0.20	0.65
Ontario	0.01	0.01	0.65
Manitoba	0.02	0.01	0.65
Saskatchewan	0.03	0.03	0.65
Alberta	0.04	0.03	0.65
British Columbia	0.70	0.50	0.65
Yukon	0.00	0.00	0.65
Northwest Territories	0.05	0.05	0.65

Note: Updated from Honer and Bickerstaff (1985).

were subtracted from the annual pest- and fire-killed areas. The disturbance matrices for salvage logging account for the combined impact of fire or insects plus logging. See *Discussion* for a sensitivity analysis of the model assumptions regarding salvage logging.

Area planted

Data describing the annually planted area were compiled from British Columbia Ministry of Forests (1951–1990), Ontario Ministry of Natural Resources (1973–1975, 1990), Manitoba Natural Resources (1987, 1992), Canadian Forestry Service (1988), Heartwell (1988), Kuhnke (1989), and Forestry Canada (1992). For most provinces, planting statistics are available only after 1975, although artificial regeneration efforts began much earlier. Anecdotal evidence indicates that planting programs began in 1940 across Canada, and, for simplicity, it was assumed that the area increased linearly from 1940 to the earliest reported values in each province. Provincial regeneration statistics were partitioned into the CBM–CFS2 spatial units within each province.

Statistics on regeneration success are very limited. Kuhnke (1989) listed estimates of regeneration success for spruce and pine plantations for the period 1983–1984 to 1985–1986. In that study, success was defined as stands reaching adequate stocking, to provincial standards, without retreatment. Stocking standards differ between administrative provinces, complicating national comparisons. Regeneration success is dependent on such factors as disturbance type, silvicultural treatments, site characteristics, competing vegetation, species planted, and weather. Given high between-year variation and unusually warm temperatures for much of the period 1980–1989 (Gullett and Skinner 1992), it is not clear whether the data for the 2-yr period reported in Kuhnke (1989) are representative of the 70-yr study period used in this analysis. It is not realistic, however, to assume a 100% planting success rate, and, in the absence of better data, Kuhnke's regeneration success estimates were applied to the reported area planted statistics.

In the model, planting is first applied to areas that have been previously clear-cut, logged, and slash burned, and all remaining planted area is allocated to the areas that were clear-cut logged. Planting is simulated in the model as a reduction in the regeneration phase from 10 to 0 yr ($n = 0$ in Fig. 1 and Table 2). It is assumed that areas planted without success regenerate naturally.

Area burned

Fire data were compiled from three sources. The publication series, Canadian Forest Fire Statistics (e.g., Ramsey and Higgins 1982, 1986, 1991, Higgins and Ramsey 1992) reported area burned annually (1980–1989) by province or territory, timber maturity class (merchantable, regeneration and immature, and cut-over/other), and fire size class. Data on area burned annually (1980–1989) by latitude and longitude for all fires >200 ha were provided by the Canadian Forest Service, Ontario Region (Stocks et al. 1996; B. Stocks, *unpublished data*). Historical data on area burned annually by province and territory (1918–1969), and by province, territory and maturity class (1970–1979) were provided by the Petawawa National Forestry Institute (D. Higgins, *unpublished data*). Data were not available for several provinces and years (Newfoundland prior to 1948; Prince Edward Island prior to 1970; and Yukon and Northwest Territories prior to 1945). Estimates for these early years were derived from the average of all available data for that province or territory (see also Van Wagner 1988).

In most provinces and years, the two data sets for the period 1980–1989 (Ramsey and Higgins 1982, 1986, 1991, Higgins and Ramsey 1992, Stocks et al. 1996; B. Stocks, *unpublished data*) are very similar, with the areas in the second data set generally somewhat smaller than the first, because it does not account for the area of fires <200 ha. In some cases, however, the second data set indicates more area burned than the first data set. The primary reason for this is that Stocks' detailed spatial statistics include fires that burned outside the zones of protection, for which some provinces (e.g., Quebec and Saskatchewan) did not maintain fire statistics in the early 1980s. In a few cases, large fires in the northern parts of these two provinces were not reported in the Canadian Forest Fire Statistics series. Area estimates for these fires were added, using information in the detailed spatial data (Stocks et al. 1996; B. Stocks, *unpublished data*).

The detailed spatial data were used to summarize the area burned by 42 spatial units and by year for the period 1980–1989. Federal statistics report the area burned by administrative province or territory (Ramsey and Higgins 1982, 1986, 1991, Higgins and Ramsey 1992). Provincial estimates were distributed among spatial units within provinces, using variable proportions. To account for the increasing role of fire suppression, the proportional distribution of fires by spatial units in each province was linearly changed in 1979 from an area-weighted distribution in 1920 to the average proportions calculated for the period 1980–1989.

This method of estimating forest fire distribution by spatial unit is equivalent to assuming that all the forest biomass on lands reported as "burned" is actually killed. In reality, small pockets of stands may survive wildfire. The assumption made here, however, is supported by a study of boreal forest fires in size classes from 20–40 000 ha (Eberhart and Woodard 1987). Eberhart and Woodard found that survival was very low and that 95–98% of the area classified as burned contained no surviving trees. Furthermore, it is recognized that small lakes, other water bodies, and areas of bedrock are included in the estimates of area burned, given that some individual fires cover many thousand

TABLE 5. Multipliers used to convert insect indicators to area killed.

Insect	Insect indicator	Multiplier
Spruce budworm	Area with moderate to severe defoliation	0.08†
Spruce budworm	Area with severe defoliation—Quebec	0.15†
Hemlock looper	Area with moderate to severe defoliation	0.05†
Jack pine budworm	Area with moderate to severe defoliation	0.05†
Mountain pine beetle	Area containing mortality	0.13‡

† J. Volney, *personal communication.*
‡ Kondo and Moody 1987, Kondo and Taylor 1984, 1985, 1986, Moody 1988, 1992, Sterner and Davidson 1981, 1982, 1983; G. A. Van Sickle, *personal communication.*

hectares. On the other hand, some small fires will have gone undetected, thus compensating for the possible overestimate of forest area affected.

Area killed by insects

The current study considers only the impacts of disturbances that are stand replacing, or that at least have a significant impact on the age structure of stands. Hence, insect infestations that only lead to reductions in stand growth rates are not explicitly considered. Such endemic insect conditions are, however, implicit in the growth functions derived from forest inventories. In the present study, insect-caused stand mortality is simulated for eastern spruce budworm *Choristoneura fumiferana* (Clem.), mountain pine beetle *Dendroctonus ponderosae* Hopk., jack pine budworm *Choristoneura p. pinus* Free., and hemlock looper *Lambdina f. fiscellaria* (Gn.), which collectively account for most forest insect losses in Canada.

Data on recent (1980–1989) insect disturbances were compiled from the Forest Insect and Disease Survey's (FIDS) annual reports published by the Canadian Forest Service (Emond and Cerezke 1990, Wood and Van Sickle 1990, Moody 1992, and many of the earlier FIDS reports). Maps from FIDS reports and annual reports from various provinces were used to assign areas, in which insect outbreaks were reported, to the spatial units within provinces. Data on historical (pre-1980) insect disturbances were compiled from Otvos et al. (1979), Blais (1983), Volney (1988); and the Canadian Forest Service (G. A. Van Sickle and C. Wood, *personal communication*). These data record the area with moderate to severe defoliation by province, year, and insect. For mountain pine beetle, the data define (by province and year) the area with some mortality or the number of trees killed. Multipliers, derived in consultation with entomologists from the Canadian Forest Service, were used to convert area defoliated or area with mortality to area insect killed (Table 5). The multipliers were based on the observation that, for many insects, successive years of attack are required to cause stand mortality, and that only a portion of the stands affected are host species for the insect. There were few data on which to base estimates of the area losses resulting from insect-induced mortality.

In principle, mortality estimates could be derived from spatially explicit maps of successive insect outbreaks, together with estimates of the probability of mortality as a function of the sequence and intensity of defoliation events and the condition and presence of host species. In the absence of adequate data, the estimates shown in Table 5 were used, although these data are acknowledged to be a simplistic representation of the dynamic processes that actually occur.

Summary of disturbance statistics

The five-year averages of the area annually disturbed by fires, insect-induced stand mortality, and clear-cut harvesting for the period 1920–1989 are summarized in Fig. 3 for various regions and for all of Canada. The graphs emphasize the regional differences in the relative importance of the disturbance types and their changes over time.

INITIAL CONDITIONS

Age class structure

The simulation of C dynamics for the period 1920–1989 requires definition of the initial conditions of the forest ecosystem carbon pools in 1920. Where stand-replacing disturbances dominate forest dynamics, as is the case in Canada, the forest age class structure is the result of disturbances during the preceding decades (Van Wagner 1978, Yarie 1981). To reconstruct the forest age class structure in 1920, three independent sets of information were combined: the forest age class structure in 1970; statistics on stand-replacing disturbances for the period 1920–1969 (Fig. 3); and a set of disturbance rules that specify how disturbances are allocated to forest types and age classes (see *Methods: Disturbances*). The age class structure in 1970, the earliest available national-scale compilation of age classes, was derived from CanFI 1981 (Bonnor 1982, 1985) and Forestry Canada (1988). This inventory has an average age of 10 yr and represents the age class structure of ~1970.

The forest age class structure in 1920 for each ecoclimatic province was reconstructed using an iterative process. The goal of the procedure was to establish a 1920 age class structure such that, after applying stand aging and the recorded stand-replacing disturbances for the period 1920–1969, the resulting simulated forest age class structure for 1970 agreed with the observations in CanFI 1981. This process required multiple iterations of modifications to the initial 1920 age class structure, followed by simulation of the period 1920–1969 using the CBM–CFS2 disturbance algorithms.

Fig. 4 shows a comparison of the national-scale age class structure derived from the NFBI for 1970, the age

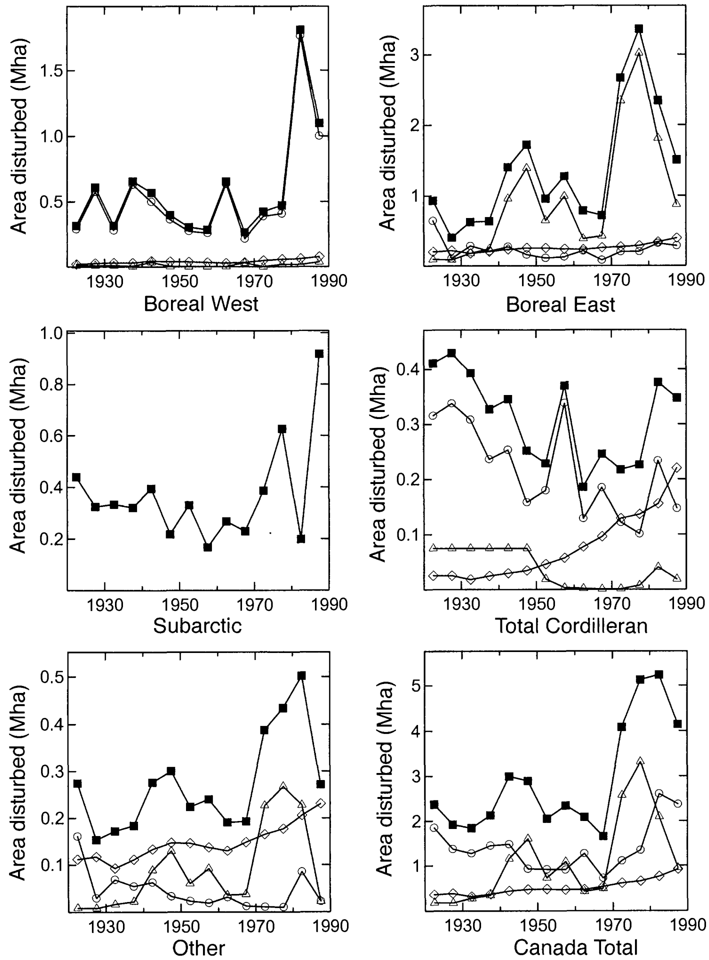

FIG. 3. The five-year averages of the area annually disturbed by fires (○), insect-induced stand mortality (△), clear-cut harvesting (◇), and the total (■) for the period 1920–1989. The total is less than the sum of the three components, because of salvage logging in areas burned or insect-killed. "Total Cordilleran" includes the Subarctic Cordilleran, Cordilleran, Interior Cordilleran, and Pacific Cordilleran ecoclimatic provinces. "Other" includes the Arctic, Cool Temperate, Moderate Temperate, and Grasslands ecoclimatic provinces. Fire is the only disturbance in the Subarctic.

class structure for 1970 obtained by simulating the period 1920–1969, and the sum of the area disturbed in the two 20-yr periods prior to 1970 (i.e., 1950–1969 and 1930–1949). The area disturbed in the 20 yr between 1930 and 1949 was estimated at 49.2 Mha, which agrees closely with the area in the 20–39 yr age class estimated from both the 1970 inventory (49.7 Mha) and the model results (47.6 Mha). The model results for the 0–19 year age class and the area disturbed in the period 1950–1969 are 40.3 and 40.6 Mha, respectively. Both are somewhat higher than the area reported in the inventory in the 0–19-yr age class (33.1 Mha). This discrepancy may reflect the time delay between actual disturbances and the next forest inventory conducted in the disturbed area, i.e., some of the recently disturbed area may not yet be included in the inventory.

The close agreement in the area estimates in the next four 20-yr age classes (40–120 yr) lends further support to the reconstructed age class structure for 1920. The total area in the remaining three age classes was estimated at 56.0 Mha by the model and 59.6 Mha in the inventory. There is, however, a discrepancy in the distribution of that area between age classes: the model underestimates the area in the 120–139 yr and in the 140–159 yr age classes and overestimates the area in the ≥160 yr age class. Most (85%) of this discrepancy arises from the Subarctic ecoclimatic province where there are few data on forest age class structures and where the model overestimates the area in the oldest age class by about 15 Mha. The forest biomass per hectare in the Subarctic is small, however, and errors in its estimated 1920 age class structure will therefore have little effect on the C dynamics estimates at the national scale.

Biomass and DOM carbon pools

Initial values for the C content (Mg C/ha) in DOM and biomass pools were assigned to each record according to the reconstructed age class structure in 1920 for each spatial unit. The age class distribution of the area varied over the 70-yr-analysis period but the total area of each ecosystem type in each spatial unit was assumed constant. Thus, for example, high productivity sites in 1970 were also assumed to be high productivity sites in 1920. The growth curves of the 457 ecosystem types (see *Methods: Biomass growth and mortality*)

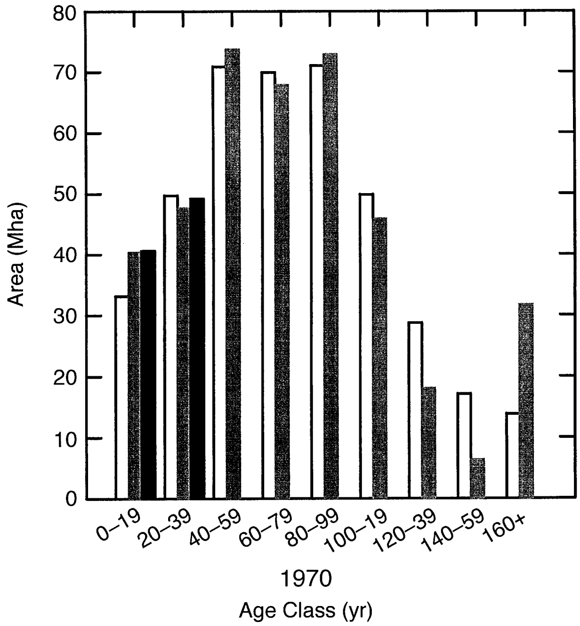

FIG. 4. The forest age class structure in Canada for 1970 derived from the Canadian Forest Inventory (CanFI) and from model simulation. Gray bars represent model results; open bars represent CanFI. For comparison, the area disturbed in the two 20-yr periods prior to 1970, i.e., 1950–1969 and 1930–1949, is shown with the 0–19 and 20–39 yr-old age classes (solid bars).

were used to calculate biomass C/ha for each ecosystem type and age class by simulating the time since the last stand-replacing disturbance.

The initial DOM C content (Mg C/ha) of each ecosystem type and age class in 1920 was obtained from data and simulation results. The setup model was used to simulate three rotations of ecosystem dynamics for each of the 457 growth types. At the beginning of the simulation, the slow DOM C pool was assigned soil C content values based on ecoclimatic province-specific soil C data taken from the ORNL global database (Zinke et al. 1986; for further details see Kurz et al. 1992, Apps and Kurz 1994). The first two rotations of stand growth were terminated by wildfire at the average age of forests in that ecoclimatic province in 1920. During the simulation of the third rotation, the average DOM C content in each age class for each of the four pools was retained in the model's database that describes the initial ecosystem conditions in 1920. In this way the initial C content in the four DOM C pools of individual model records are derived from simulated biomass input through litterfall and mortality, organic matter decomposition, and disturbance impacts. Alternative assumptions about DOM C contents in 1920 will be discussed in the *Discussion.*

Summary of methods

Fig. 5 summarizes the methods and main sources of data used to establish the initial conditions for 1920 and to simulate C dynamics during 1920–1989. The

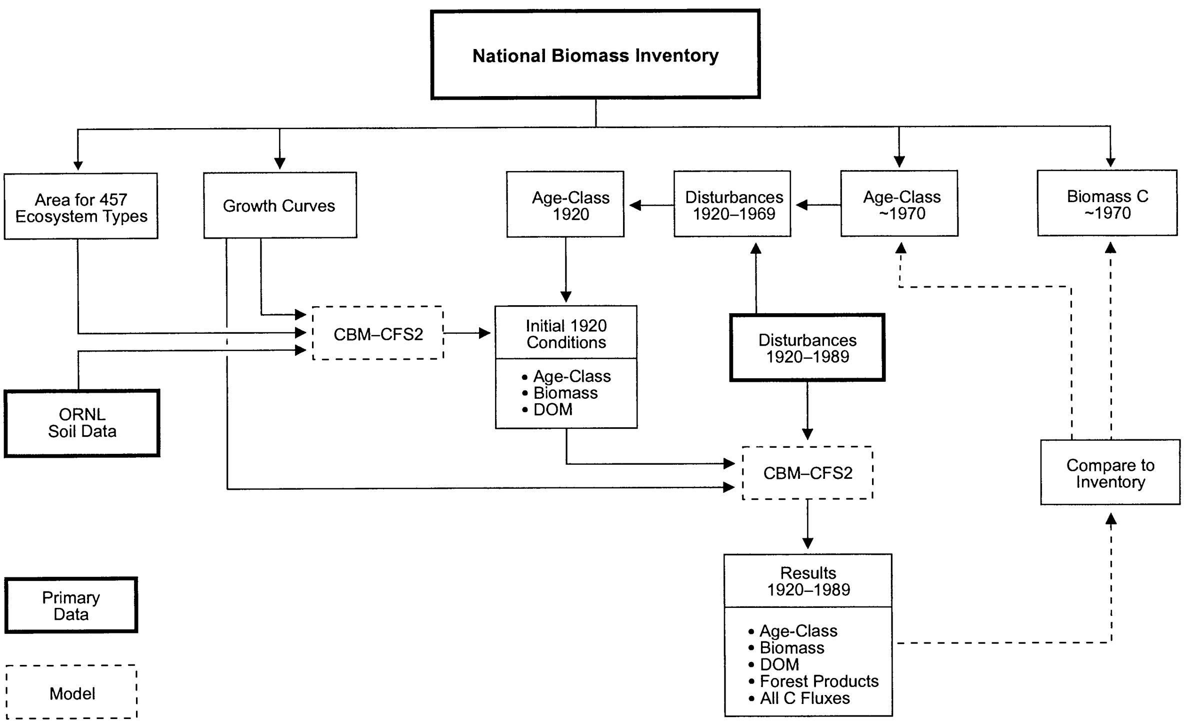

FIG. 5. Flow chart summarizing input data and their use to set up initial conditions (1920) and to conduct the retrospective analysis.

TABLE 6. Carbon content estimates (Mg C/ha) for forest area in eleven ecoclimatic provinces, and average for Canada, for 1989.

Pool	Canada	Boreal West	Boreal East	Subarctic	Cool Temperate	Moderate Temperate	Grassland	Cordilleran	Interior Cordilleran	Pacific Cordilleran	Subarctic Cordilleran	Arctic
Biomass												
SW: Aboveground	22.0	17.3	11.2	12.4	18.6	30.0	2.3	48.9	66.9	110.8	8.9	9.3
Belowground	5.1	4.0	2.6	2.9	4.3	5.0	0.4	11.4	15.6	25.8	2.2	1.5
Total softwood	27.2	21.3	13.8	15.3	22.9	35.0	2.7	60.3	82.5	136.7	11.1	10.8
HW: Aboveground	6.4	7.9	4.1	1.7	25.5	94.9	24.7	7.2	3.6	4.7	1.1	1.5
Belowground	2.4	3.2	1.8	1.0	6.1	20.0	7.7	2.7	1.5	1.4	1.1	1.5
Total hardwood	8.8	11.1	5.9	2.7	31.6	114.9	32.4	9.8	5.1	6.1	2.2	3.1
Total aboveground	28.4	25.2	15.3	14.1	44.1	124.9	27.0	56.0	70.5	115.5	10.0	10.8
Total belowground	7.5	7.2	4.4	3.9	10.5	25.0	8.1	14.1	17.1	27.3	3.3	3.1
Total biomass	35.9	32.4	19.7	18.0	54.5	149.9	35.5	70.1	87.5	142.7	13.4	12.3
Dead organic matter (DOM)												
Very fast	6.9	8.2	4.6	8.8	4.4	5.0	5.0	8.3	5.9	5.6	12.2	18.5
Fast	17.1	15.7	16.1	12.3	20.1	35.0	10.8	24.5	26.3	31.0	8.9	20.1
Medium	10.2	7.4	9.9	7.3	23.3	15.0	8.9	11.3	12.6	24.3	4.5	3.1
Slow	142.4	107.0	114.6	219.7	117.6	134.9	67.9	141.4	191.6	171.1	198.2	209.8
Total DOM	176.5	138.3	145.1	248.1	165.4	189.9	93.0	185.5	236.4	231.8	223.8	251.5
Ecosystem												
Total	212.4	170.7	164.8	266.1	220.0	339.8	128.1	255.7	323.9	374.6	237.2	265.4

Notes: See *Methods: Biomass growth and mortality* for definition of biomass C pools, and see *Methods: Dead organic matter dynamics* for definition of DOM C pools. HW = hardwood; SW = softwood.

NFBI was used to derive four sets of information: forest area in each of 457 ecosystem types (see *Methods: National stratification*); growth curves describing the aboveground biomass dynamics for softwood and hardwood species group in each of the 457 ecosystem types (see *Methods: Biomass growth and mortality*); the age class structure in 1970 that is used in conjunction with the disturbance statistics for the period 1920–1969 to reconstruct the age class structure of 1920; and a biomass C estimate for ~1970. Note that the biomass C estimates from the NFBI are not used as input to the model. The estimates of soil organic matter content (Zinke et al. 1986) are combined with the simulation of ecosystem dynamics to obtain estimates for initial soil C pool sizes in 1920. The CBM–CFS2 uses initial conditions for 1920 and the disturbance statistics for the period 1920–1989 to simulate changes in C pools and fluxes. The model's estimates of the age class structure in 1970 and the biomass C pools in 1970 are compared to the statistics in the NFBI.

RESULTS

Biomass and DOM carbon estimates

Biomass and DOM C content (Mg C/ha) vary over time and with ecoclimatic province. Table 6 summarizes the C estimates derived from the model for the endpoint (1989) of the 70-yr simulation. The average biomass C content for Canadian forest ecosystems in 1989 was 35.9 Mg C/ha, of which 28.4 Mg C/ha was in aboveground living biomass and 7.5 Mg C/ha in fine and coarse root biomass. High average biomass C contents were found in the Pacific Cordilleran (143 Mg C/ha, dominated by softwood biomass), and in the Moderate Temperate ecoclimatic province (150 Mg C/ha, dominated by hardwood biomass).

The average DOM pool C content in 1989 was 177 Mg C/ha, of which 142 Mg C/ha (81%) was in the slow DOM C pool, which represents humified soil organic matter. High DOM C contents were found in those ecoclimatic provinces that have low mean annual temperatures (Arctic, Subarctic, and Subarctic Cordilleran) and in those regions where productive forests provide large quantities of biomass input (Pacific Cordilleran and Interior Cordilleran). The model estimate of average C content in Canadian forest ecosystems (excluding peat C) was 212 Mg C/ha of which 17% is in biomass and 83% in DOM C pools.

Ecosystem dynamics

Most of Canada's forests are classified as even-aged stands and <1% of the area in Canada's forests is classified as uneven-aged (Bonnor 1985, Lowe et al. 1994). Stand-replacing disturbances such as wildfire or clearcut logging reset the age of the affected forest stands to zero. The age class structure of the forest is therefore a useful indicator of the population dynamics of the stands.

The model results indicate that the average age (Fig. 6) and the age class structure (Fig. 7) of Canada's forests have been changing during the 70-yr period of this retrospective analysis. In 1920, the average age of Canadian forests was 59.0 yr, and the age class distribution (Fig. 7a) suggests high disturbance rates during the late 19th and early 20th century (a large proportion

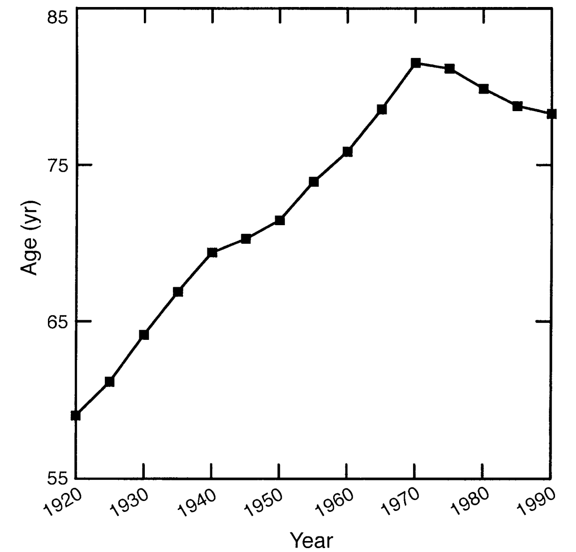

FIG. 6. The change in the average forest age in Canada for the period 1920–1989.

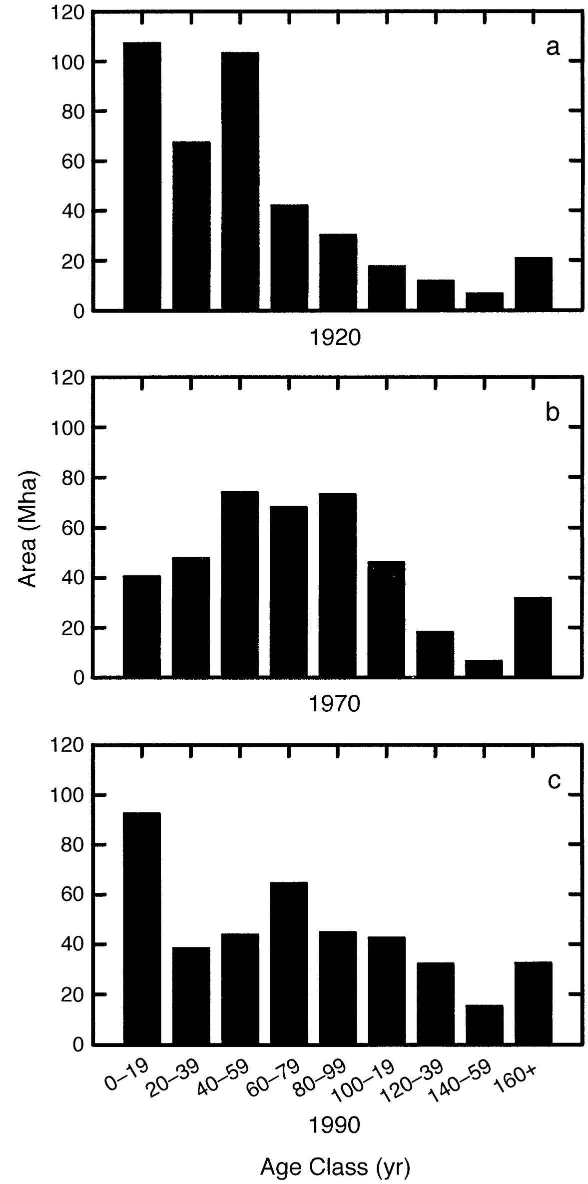

FIG. 7. The distribution of Canadian forest area in 20-yr age classes in 1920, 1970, and 1990 (adapted from Kurz et al. [1995]).

of the 1920 forest was <60-yr-old). This inference is supported by the CanFI data (Fig. 4), which show that in 1970 most forest area was in the 40–100 yr age classes. Over the 50-yr period (during 1920–1969) the average forest age increased to 81.5 yr, indicating that, during this period, disturbance rates (Fig. 3) were lower than during the latter half of the previous century. Fewer disturbances caused the forest age class distribution to shift to the right (Fig. 7b). In the last 20 yr of the analysis period (1970–1989), reported disturbance rates more than doubled (Fig. 3). The forest area in the youngest age class increased (Fig. 7c) and the average forest age decreased to 78.2 yr. This increase in the area in the youngest age class is also starting to appear in recent provincial and national forest inventories (Ontario Ministry of Natural Resources 1992, Lowe et al. 1994) but since these inventories are only updated periodically, the effects of the most recent disturbances are not yet fully captured.

Ecosystem carbon fluxes

The annual change in ecosystem C is, by definition, the sum of the changes in biomass and DOM C pools. The change in the biomass C pool is the sum of net tree growth prior to accounting for disturbance impacts and the losses (biomass transfers) associated with disturbances. Biomass transfers to the soil pools, the forest product sector, and disturbance releases to the atmosphere are all explicitly accounted for in the CBM–CFS2. The change in the DOM C pool is the sum of litterfall inputs, decomposition releases, and the transfers associated with disturbances. Disturbance transfers include those from biomass to DOM C pools, as well as releases to the atmosphere associated with, for example, combustion of the litter layer during a fire.

The contributions by each flux to the net change in the biomass pools are summarized at the national scale in Fig. 8a. The uptake of biomass C through tree growth averaged 217 Tg C/yr (1 Tg = 10^{12} g). This uptake slowly declined over the 70-yr period, as a result of the changes in the age class structure of the forest. The largest flux out of the biomass pool has been the transfer of biomass to DOM pools associated with disturbances (124 Tg C/yr). This transfer was high during the 1940s and again during the last 20-yr period, a direct result of the disturbance regimes (see Fig. 3). Over the seven decades, the transfer of biomass C to the forest product sector averaged 27 Tg C/yr. The 5-yr average increased over the period of record, rising

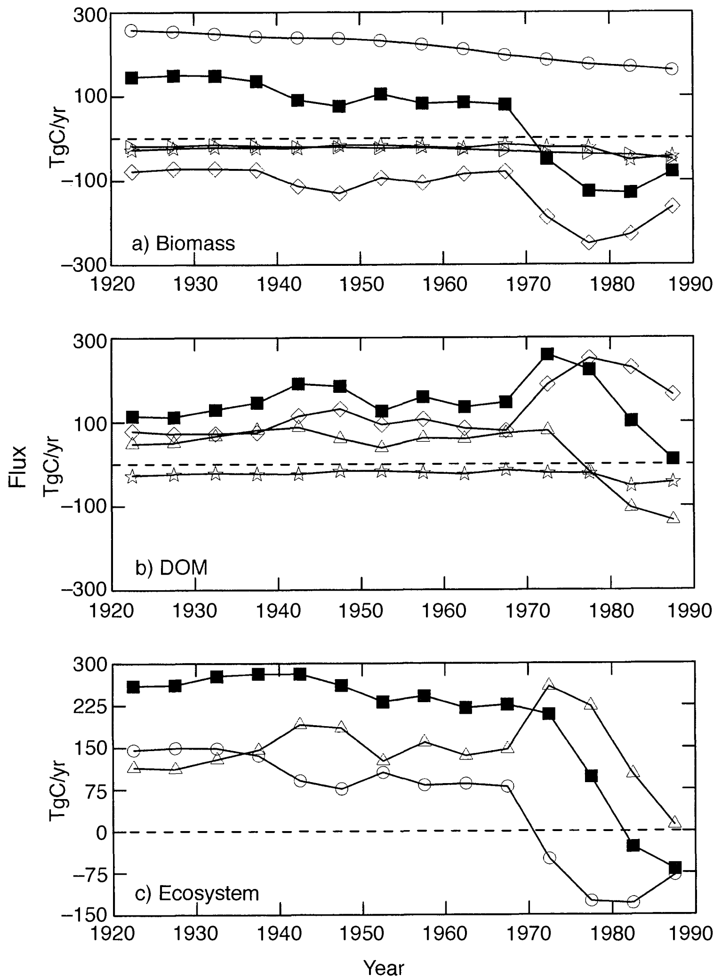

FIG. 8. Major fluxes contributing to the changes at the national scale in (a) the biomass C pool; (b) the DOM C pool; and (c) total ecosystem C. (a) Biomass fluxes: harvest (▷), disturbance release to the atmosphere (☆), biomass to DOM transfer (◇), biomass growth before disturbances (○), and the annual change in the biomass pools (■). (b) DOM fluxes: disturbance release (☆), biomass to DOM transfer (◇), net litterfall, i.e., the balance of decomposition releases and litterfall inputs (△), and the annual change in the DOM pools (■). (c) Ecosystem fluxes: changes in the biomass pool (○), changes in the DOM pools (△), and total ecosystem change (■).

from 19 Tg C/yr in 1920–1924 to 50 Tg C/yr in 1985–1989. The direct release of biomass C to the atmosphere (as a consequence of disturbances, primarily fire) averaged 15 Tg C/yr over the 70-yr period.

Fig. 8b shows the fluxes associated with changes in the DOM C pools. Net litter accumulation—i.e., litterfall inputs (not accounting for the transfers associated with disturbances) minus decomposition releases—is estimated to have averaged 63 Tg C/yr in the period 1920–1970. Net litter accumulation changed to a loss (−45 Tg C/yr) in the last 20 yr of the analysis period. In the first 50 yr of the record, disturbances transferred 91 Tg C/yr from biomass to DOM pools. This increased to 208 Tg C/yr in the last 20 yr. The 5-yr average of the disturbance release from wildfires and slash burning of C from DOM pools ranged 7–22 Tg C/yr and averaged 11 Tg C/yr over the 70-yr period.

Net changes in ecosystem C pools (Fig. 8c) are the combined changes in biomass (Fig. 8a) and DOM C pools (Fig. 8b). The average annual change in ecosystem C over the 70-yr period was 205 Tg C/yr. In the first 50 yr, the net increase was 254 Tg C/yr. Uptake from the atmosphere decreased to an average of 52 Tg C/yr in the last 20 yr. In the period 1985–1989, the C content in Canada's forest ecosystems was estimated to have decreased by 69 Tg C/yr.

The results reported here focus on Canadian forest ecosystems and do not include the analysis of the fate of harvested material in the forest product sector. A portion of the C removed from the ecosystems has been retained in the forest product sector and, over the 70-yr period, the forest product C pool (including landfills) steadily increased (Kurz and Apps, *unpublished data*).

Ecosystem carbon pools

In 1989, biomass C pools contained an estimated 14.5 Pg C in aboveground (11.5 Pg C) and belowground (3.0 Pg C) biomass. The two boreal ecoclimatic provinces and the three cordilleran ecoclimatic provinces contained most of this C (Fig. 9). The DOM C pools in 1989 contained an estimated 71.4 Pg C, most of which (57.6 Pg C) was in the slow DOM C pool. The largest DOM C pools were found in the Subarctic ecoclimatic province and the two boreal ecoclimatic prov-

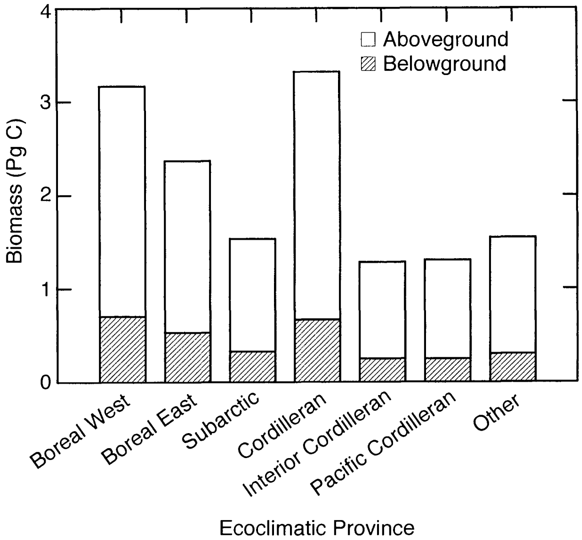

FIG. 9. Above- and belowground biomass (Pg C) in the ecoclimatic provinces of Canada in 1989. "Other" combines the results for five ecoclimatic provinces: Arctic, Cool Temperate, Moderate Temperate, Grassland, and Subarctic Cordilleran.

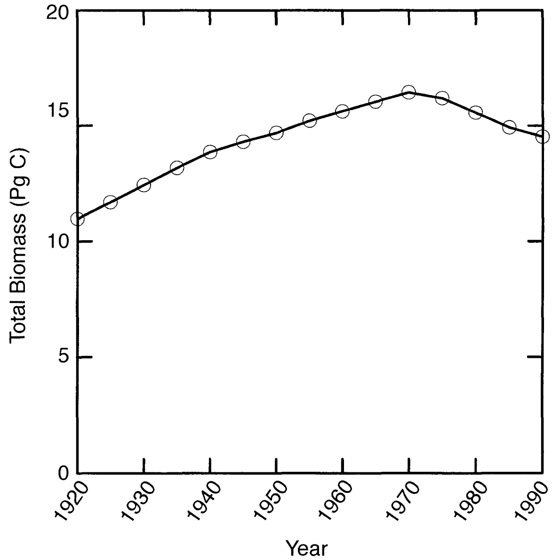

FIG. 11. The total (above- and belowground) biomass C pool of Canadian forests during 1920–1989 estimated by CBM–CFS2.

inces (Fig. 10), which also account for 75% of the total area (Tables 1 and 6).

The C fluxes resulted in significant changes in biomass and DOM C pools. Total biomass (i.e., above and belowground) increased from 11.0 Pg C in 1920 to 14.5 Pg C in 1990 (Fig. 11). The biomass C pool was greatest in 1970, when it contained an estimated 16.4 Pg C in total biomass and 13.0 Pg C in aboveground biomass.

The CBM–CFS2 results indicate that DOM pools have increased from 61.2 to 71.4 Pg C over the 70-yr period of the analysis (Fig. 12). This increase (10.2 Pg C) was distributed unevenly across the four DOM C pools (Table 7). Each DOM C pool displays different dynamics (Fig. 12). The very fast pool increased until about 1975, but then decreased as disturbance rates increased. The fast pool, which contains branches, treetops, and small diameter stem wood, showed the largest percent increase (70%). Like the very fast pool, the fast pool increased for most of the analysis period, but

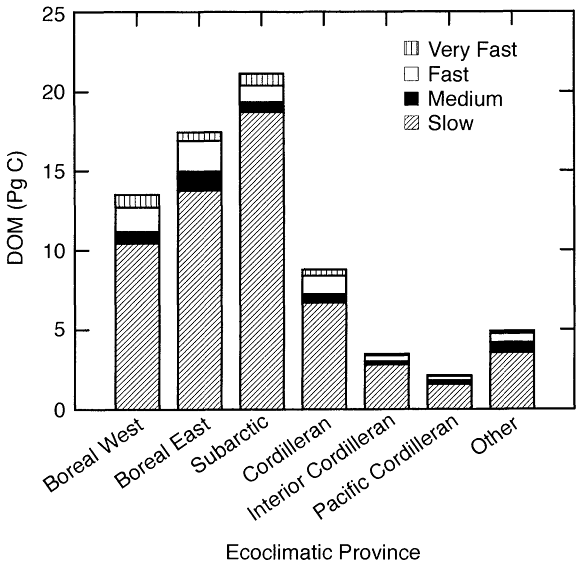

FIG. 10. Carbon in four DOM C pools (Pg C) in the ecoclimatic provinces of Canada in 1989. "Other" combines the results for five ecoclimatic provinces: Arctic, Cool Temperate, Moderate Temperate, Grassland, and Subarctic Cordilleran.

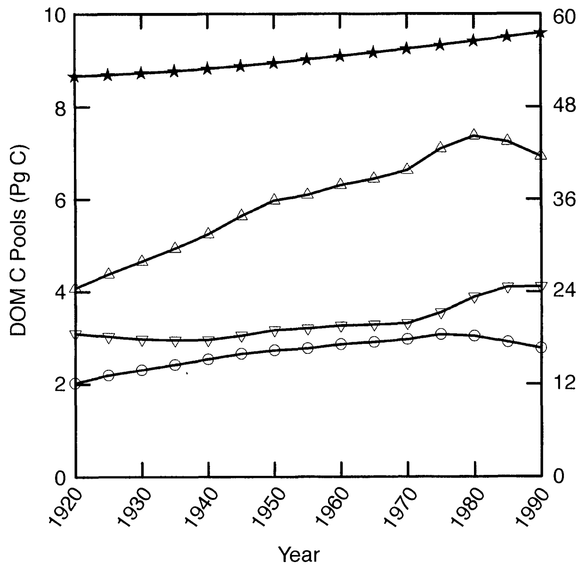

FIG. 12. The four DOM C pools of Canadian forests during 1920–1989 estimated by CBM–CFS2. Symbols are for the very fast (○), fast (△), medium (▽) and slow (★, plotted against right y-axis) DOM C pool.

TABLE 7. Summary of DOM C pools in 1920 and 1989, and changes over the 70-yr period.

DOM pool	Pool size (Pg C)		Total change		Annual change	
	1920	1989	(Pg C)	(Percent)	(Tg C/yr)	($g \cdot m^{-2} \cdot yr^{-1}$)
Very fast	2.0	2.8	0.8	37	10.8	2.7
Fast	4.1	6.9	2.9	70	40.7	10.1
Medium	3.1	4.1	1.0	33	14.5	3.6
Slow	52.0	57.5	5.6	11	79.4	19.6
Total	61.2	71.4	10.2	17	145.5	36.0

decreased during the last 10 yr, the decade with the most wildfires. The medium pool, which contains stem wood of merchantable size, showed little change during the first 50 yr of the period, but increased rapidly during the last 20 yr, when insect and fire disturbances increased. The increases in DOM litter pools resulted in a slow but monotonic increase in the slow DOM C pool, which receives input solely through decomposition of the other pools (Fig. 2). The slow pool increased by 11% over the 70-yr period, but this relatively small increase accounted for 5.6 Pg C of additional C storage.

As with biomass, the initial (1920) conditions for all four DOM C pools are affected by the disturbance history prior to 1920. The age class structure inferred for the forests in 1920 indicates high disturbance rates in the decades before 1920. The 50-yr period (1920–1969) of relatively low disturbances resulted in an increase in the average age of the forest, which was accompanied by an increase in the C stored in litter and detritus pools. The increase in disturbances in the last 20-yr period greatly increased the transfer of biomass to DOM C pools (Fig. 8b). As these pools increased, the postdisturbance release of C through decomposition also increased: in the period 1985–1989, decomposition releases exceeded litterfall inputs by 149 Tg C/yr (Fig. 8b).

DISCUSSION

The results presented here are based on the CBM–CFS2 simulation model. It uses data from several large databases (Fig. 5) to simulate forest dynamics over a period of 70 yr for >400 Mha of forest. Given the time and space scales of the analysis, a direct validation of all model results is not possible. However, several comparisons can be made to assess the veracity of the simulation results.

Biomass dynamics are a critical part of the model simulation, and two comparisons with independent results are presented as partial validation of the CBM–CFS2. The NFBI (Bonnor 1985) describes conditions for ~1970 and an estimate for ovendry aboveground biomass of 26.1 Pg (1 Pg = 10^{15} g). The CBM–CFS2 estimate of aboveground biomass in 1970 was 13.0 Pg C, equivalent to 26.0 Pg ovendry aboveground biomass, using the biomass-to-C conversion factor of 0.5. Simulation of C dynamics for the period 1920–1969 thus yields an estimate for the aboveground biomass C pool in 1970 that is consistent with the value reported in the static NFBI.

Using independent measurements, Simpson et al. (1993) reported the aboveground biomass C content in the North American boreal forest to be 18.8 ± 4.5 Mg C/ha. The CBM–CFS2 simulation results for 1989 indicate aboveground C contents of 14.1, 15.3, and 25.2 Mg C/ha for the Subarctic, Boreal East, and Boreal West ecoclimatic provinces, respectively. The area-weighted average aboveground biomass C content for the three ecoclimatic provinces in 1989 of 18.2 Mg C/ha agrees well with the results reported by Simpson et al. (1993).

Confidence in the simulation of harvest disturbances can be gained by comparing simulated harvest removals from the forest ecosystems with the actual data. Historical estimates of forest harvesting in Canada were used to define the disturbance rules that are simulated in the model. These data provided estimates of the volume harvested and, for recent years, of the actual area harvested. The simulation estimates of the biomass C removed in harvest, which invoke all the disturbance allocation rules, salvage logging, and simulated changes in biomass over time in each spatial unit, are compared with the historical harvest volume data for all of Canada (Fig. 13). The CBM–CFS2 consistently overestimates the harvested volume by a small amount; estimates of cumulative harvest for the 70-yr period are 7.5×10^9 m^3, which is 8.7% higher than the data suggest (6.9×10^9 m^3).

Comparison of CBM–CFS2 estimates of forest productivity with other reported estimates is complicated by differences in the spatial scale considered by the different authors. Distributed across all of the forested area of Canada, the average annual increase in biomass pools obtained with the CBM–CFS2 was 12.6 g $C \cdot m^{-2} \cdot yr^{-1}$ over the 70-yr period. Net biomass growth prior to disturbances averaged 53.6 g $C \cdot m^{-2} \cdot yr^{-1}$ over the 70-yr period and was 39.7 g $C \cdot m^{-2} \cdot yr^{-1}$ in the period 1985–1989. This estimate of biomass accumulation rates can be compared with the estimates of pulpwood volume mean annual increment (m.a.i.) obtained from CanFI 1991 (Lowe et al. 1994). Assuming that pulpwood accounts for 50% of the total biomass, or 63% of aboveground biomass (M. Penner, *personal communication*), and a conversion factor of 4.0 for volume to C (average biomass density of 0.5 g biomass/cm^3

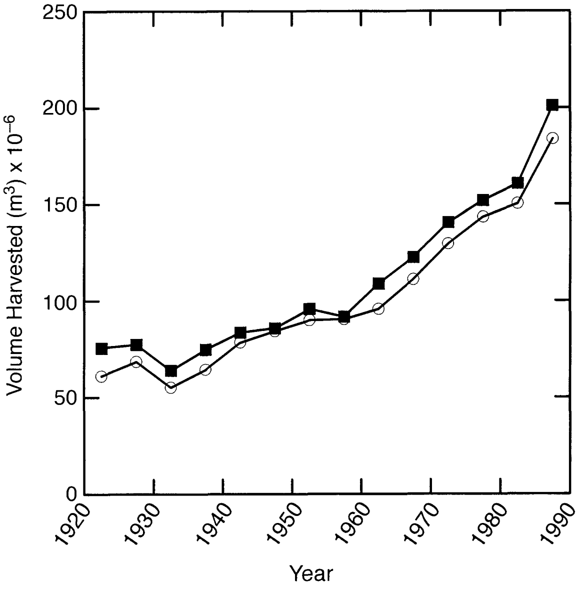

FIG. 13. The 5-yr average of the annual harvest in Canada from historical data (○) and model simulation results (■).

and average biomass C content of 0.5 g C/g biomass), this latter estimate of the annual increase in biomass pools is approximately equal to a net increase in pulpwood volume of 0.8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. At first sight, this does not appear to compare favorably with the Lowe et al. (1994) estimate of 1.59 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for m.a.i. in pulpwood volume in the stocked productive forests of Canada (228.7 Mha). The lower CBM–CFS2 estimate is, however, derived from both the productive and unproductive forest area (404.2 Mha), three-quarters of which is in the boreal ecoclimatic provinces (Table 1). Estimates of net ecosystem productivity (NEP) for the Canadian boreal forest derived from the CBM–CFS2 compared favorably with Bonan's (1991) estimates derived for an area of the boreal forest near Fairbanks, Alaska, USA (Kurz and Apps 1996).

The CBM–CFS2 estimates of DOM C pool sizes and their dynamics are associated with the largest uncertainties in the model. The source of this uncertainty lies in the parameters defining the decomposition rates, for which there are very limited data, and in the initial values assigned to the DOM pools. The emphasis of the CBM–CFS2 analysis presented here has been on estimating the annual net C flux between Canada's forest ecosystems and the atmosphere. DOM C pool estimates are associated with considerable uncertainties, but the important question is the following: How much do these uncertainties in pool sizes influence the estimated changes in these pools? These changes determine the DOM contribution to the net ecosystem flux.

After completion of the initial study, an opportunity arose to examine this uncertainty by using a new soil C database. Apps and coworkers have compiled a soil C database with 1469 data points for all of Canada (hereafter referred to as the CFS database; Siltanen et al. 1997). For comparison, the ORNL global C database, which is used in the CBM–CFS2 analysis presented here, contained 117 entries for Canada. Both databases include soil organic C to a depth of 1 m, but neither includes coarse woody debris. Soil C content estimates by ecoclimatic province for the two databases differ substantially.

An alternative parameterization of the DOM components of the model was constructed from the CFS database to assess the sensitivity of net ecosystem C flux estimates to changes in DOM C pool sizes. The initial conditions for DOM C pools and decomposition rates in each ecoclimatic province were adjusted to bring the C content estimates from the model into agreement with the estimates derived from the new CFS database. To achieve this agreement in DOM C pools, it was necessary to modify the DOM C decomposition rates by factors in the range 0.8–3.4 (the unweighted average decomposition rate multiplier for the 11 ecoclimatic provinces was 1.7). To establish the new initial (1920) DOM C values for the reparameterized CBM–CFS2, the steps outlined in *Initial conditions: Biomass and DOM C pools* were followed, except that the soil C content estimates from the CFS database were used to initialize the slow DOM C pool at the beginning of the three simulated rotations. A simulation of the period 1920–1989 was then performed with the reparameterized model using the new DOM initial values and adjusted decomposition rates. All other conditions and parameters were as previously described. The DOM C content estimates in the two databases were compared to the CBM–CFS2 estimates of DOM C, excluding the medium turnover pool, which contains coarse woody debris. The CBM–CFS2 estimates for DOM pool sizes and fluxes obtained under the two different parameterizations were compared to examine the model's sensitivity to initial DOM pool values and decomposition rates.

Fig. 14 summarizes DOM C content estimates derived from the Zinke et al. (1986) database, the estimates derived from the base model run initialized with these data, the estimates from the CFS soil C database, and the results from the reparameterized model. The DOM C content estimates derived from the reparameterized model are in close agreement (±3%) with the new database estimates, because the decomposition rates were adjusted to reach this agreement.

The revised parameter values reduced the total DOM C content in 1989 by 35% (Table 8). Changes between the base run and the reparameterized run for individual ecoclimatic provinces ranged from −63 to +80%.

What are the implications of these changes in DOM C pools to the net ecosystem fluxes? Fig. 15 summarizes the net C flux in Canada's forest ecosystems for the period 1920–1989 for the two simulations. The reduction in DOM C pool size associated with the reparameterization also decreased ecosystem C uptake

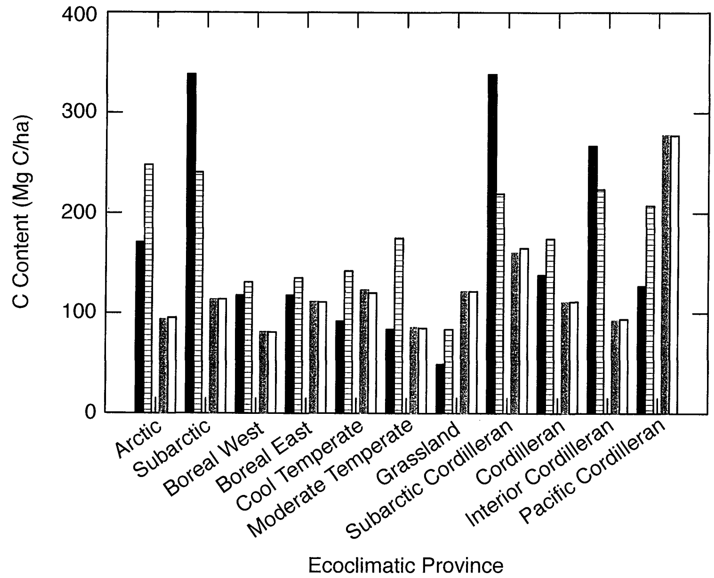

FIG. 14. DOM C content (Mg C/ha), by ecoclimatic province, based on two independent soil databases and model results. For each ecoclimatic province, the bars (from left to right) are as follows: solid bars, data from Zinke et al. 1986; horizontally hatched bars, CBM–CFS2 base run results for 1989; shaded bar, data from Siltanen et al. 1997; and open bar, recalibrated CBM–CFS2 results.

from 13.7 to 11.8 Pg C (14%) over the 70-yr period. More importantly, however, the overall pattern of the C dynamics was not significantly affected by this change in assumptions about DOM pool sizes and decomposition rates. Although further research is needed to better quantify soil and detritus C pool sizes and dynamics in Canadian forests (Trofymow et al. 1995), the important conclusion from this analysis is that the CBM–CFS2 estimates of net ecosystem C fluxes, and their change over the 70-yr period, are fairly insensitive to uncertainties in the estimates of DOM C pool sizes.

Another area of uncertainty involves the assumptions about salvage logging and their effects on the national C budget. Salvage logging is conducted to remove merchantable biomass from areas previously disturbed by fire or insects, hence the total area affected by all disturbance types is less than their sum. To examine how much of an effect errors in salvage logging could have, a model run without any salvage logging was conducted. In the model, this forces all harvesting to take place in areas not recently affected by fire or insects and thereby causes an increase in the total area disturbed.

Elimination of all simulated salvage logging decreased ecosystem C accumulation during 1920–1989 by 4.5% (from 13.7 Pg C in the base run to 13.1 Pg C in the sensitivity analysis run). Therefore, overestimating the area that is salvage logged increases the estimated C accumulation in ecosystem pools, because the total area disturbed is reduced. The uncertainties in estimates of salvage logging do not, however, greatly affect the CBM–CFS2 estimates of net ecosystem C flux.

The results of the analysis are sensitive to errors in

TABLE 8. Summary of the DOM C pools (Pg C) in the forest area in each ecoclimatic province and for all of Canada for the base run and reparameterized run of CBM–CSF2.

Ecoclimatic province	DOM C (Pg C) Base run 1920	DOM C (Pg C) Base run 1989	DOM C (Pg C) Reparameterized run 1920	DOM C (Pg C) Reparameterized run 1989	Percent change 1920	Percent change 1989
Arctic	0.15	0.16	0.06	0.06	−61%	−62%
Subarctic	21.29	21.15	9.23	10.09	−57%	−52%
Boreal West	10.36	13.50	6.13	8.36	−41%	−38%
Boreal East	13.99	17.45	11.65	14.26	−17%	−18%
Cool Temperate	3.13	4.26	2.83	3.51	−10%	−18%
Moderate Temperate	0.03	0.04	0.01	0.02	−50%	−50%
Grasslands	0.15	0.24	0.27	0.34	80%	41%
Subarctic Cordilleran	0.20	0.20	0.14	0.15	−31%	−24%
Cordilleran	7.08	8.78	4.51	5.56	−36%	−37%
Interior Cordilleran	3.18	3.46	1.19	1.45	−63%	−58%
Pacific Cordilleran	1.61	2.12	2.34	2.80	45%	32%
Total	61.17	71.36	38.35	46.61	−37%	−35%

Note: The last two columns indicate the percent change in pool sizes resulting from the alternative assumptions about decomposition rates.

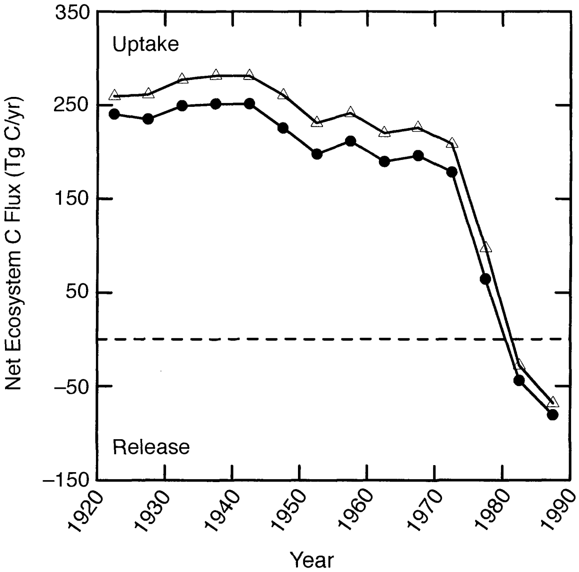

FIG. 15. Annual change in ecosystem C pools during 1920–1989 for the base run (△) and the reparameterized model run (●).

the statistical record of stand-replacing disturbances in the period 1920–1989. The quality of the disturbance data is expected to be lowest in earlier years of the analysis period. To assess the possible error in the disturbance record, the age class data contained in CanFI were examined. The two left-most groups of bars in Fig. 4 indicate that, for the two 20-yr periods 1930–1949 and 1950–1969, the total area of stand-replacing disturbances is equal to or somewhat greater than the area in the age classes originating from these disturbances. The forest area in the youngest age class can be expected to be an underestimate and, thus, smaller than the sum of the area disturbed during the preceding 20 yr, because some recently disturbed areas may not have been included in the most recent inventory cycle. The total area disturbed, however, is of the right magnitude, at least as far back as 1930, but this does not preclude residual errors in the partitioning of disturbances among the main disturbance types. Thus, for example, possible underestimates of fire disturbances could be compensated in the model by overestimates in insect disturbances. Since fire and insect estimates were obtained from independent sources, this would be an unlikely coincidence of compensating errors. Moreover, shifts in the partitioning of disturbance types in a given year will affect fluxes in the short term (because fires, compared to insects, release more C at the time of disturbance), but will not have large effects on the longer term dynamics.

Biomass removed from forest ecosystems is transferred to the forest product sector. The CBM–CFS2 framework includes a forest product sector submodel (CBM–FPS) that accounts for the fate of the harvested C (Kurz et al. 1992). The CBM–FPS is described in a separate manuscript (Apps et al., *in press*).

The CBM–CFS2 does not explicitly simulate the effects of changes in temperature, precipitation, or atmospheric CO_2 concentration on growth or decomposition. In an earlier sensitivity analysis, the extent to which such environmental changes may affect future C budgets of Canadian forests was examined with the CBM–CFS2 (Kurz and Apps 1994). In that study, the sensitivity of Canadian forest C budgets to different scenarios of changes in disturbance regime, site carrying capacity, growth rates, and decomposition rates was examined. The analysis indicated that changes in disturbance regimes were likely to have as large, or larger, effects on C exchanges with the atmosphere as climate-induced changes in site carrying capacity or growth rates. For this reason, the primary effort in CBM–CFS2 development to date has been devoted to examining the influence of known, and documented, changes in the incidence of stand-replacing disturbances. Moreover, to some extent, forest ecosystem response to environmental change is already present in the CBM–CFS2 parameterization of growth curves. For the retrospective analysis presented here, it was assumed that stand growth dynamics over the 70-yr period are similar to those derived from the NFBI. If the changes in environmental conditions during the 70-yr period have influenced forest growth dynamics, their effect may already be accounted for in the inventory, and be partially reflected in the growth curves used by the model, but none of these changes over time will be captured in the present formulation. For this reason, the present implicit representation of environmental response is inadequate for reliable future projections, except by using prescribed response scenarios (e.g., Kurz and Apps 1994, 1995). A challenge for future work with the CBM–CFS2 will be to incorporate process level responses to changes in these environmental variables (Price and Apps 1993).

The decade of the 1980s has been the warmest decade on record in Canada (Gullet and Skinner 1992). These warmer temperatures may have affected wildfire and insect disturbances, which would be accounted for in the disturbance statistics. The calculation of decomposition rates incorporates estimates of mean annual temperature derived from the climate normals (i.e., the averages of the period 1951–1980). Any deviations from the climate normals during the 70-yr-analysis period may have also affected decomposition and growth rates, but these influences are not accounted for in the current analysis. Work is in progress to estimate temperature change effects on the forest sector C budget over the 70-yr period.

Land use change, such as the conversion of forest to agricultural land, plays an important role in many national C budgets (e.g., Houghton et al. 1983, 1987), but this does not appear to be a significant factor for the Canadian forest land base (Greenough et al. 1997).

In Canada, the area of improved agricultural land increased by 16.9 Mha from 28.7 Mha in 1920 to 45.6 Mha in 1990 (McCuaig and Manning 1982; Statistics Canada 1992 and the series of similar publications for each province). In 1990, the three prairie provinces (Alberta, Saskatchewan, and Manitoba) contained 84% of the agricultural area in Canada. Most of this land was derived from the conversion of grassland ecosystems, not forests. In the three prairie provinces, the agricultural land area increased by 20.3 Mha in the period 1920–1990. Since the total increase in improved agricultural land in Canada during this time was 16.9 Mha, agricultural land area must have decreased in some of the other provinces. Some of this abandoned agricultural land will undoubtedly have returned to forest, but the area involved is a small proportion (≤1%) of the total forest land base. In total, the net effects of land-use changes from forests to agriculture, and vice versa, are not considered to have significantly affected the forest sector C budget at the national scale, although regional effects could be significant.

Conclusions

The CBM–CFS2 results suggest that forest ecosystems in Canada have been a sink of atmospheric C for the period 1920–1980. In the decade of the 1980s, ecosystem C decreased as a result of a >twofold increase in the area annually affected by stand-replacing disturbances, primarily of natural origin. The forest age class distribution for 1970, derived from the national inventories and the reconstructed forest age class distribution for 1920, suggest that the area annually disturbed in the period 1860–1920 was greater than that in the 70 yr of this analysis. Changes in forest disturbance regimes have resulted in an increase of the average age of Canadian forests over the period 1920–1980. These changes have also resulted in an increase of the C content of both biomass and DOM C pools. Note that this shift in age class structure is not the result of regrowth from harvesting.

The estimates of the biomass C content and pool sizes presented here are consistent with those obtained in independent studies (Bonan 1991, Simpson et al. 1993). Considerable uncertainties remain, however, regarding the size of the DOM C pool. Sensitivity analyses showed that significant changes in DOM C pool sizes associated with two different soil databases did not greatly affect the numerical estimates of ecosystem C fluxes by the CBM–CFS2, and the size changes left the temporal trends in these fluxes essentially unchanged. Several other sources of uncertainty in the model were similarly examined, and, in each case, the estimates of net ecosystem C fluxes were found to not be greatly affected.

The primary factor underlying the C sink to ~1970 was a change in the disturbance frequency over a time scale of many decades, which resulted in changes in the average forest age and C content. As the average forest age increases, the ability to sequester additional C decreases, and the susceptibility to disturbances increases. It is therefore not likely that this forest sector C sink could be sustained by maintaining a low disturbance rate through forest protection measures. Indeed, the changes of the last two decades of the analysis period, whether due to human-induced climatic change or natural variation, have resulted in significant changes in the disturbance regimes, relative to the preceding half century. These disturbances have decreased the forest sector C sink and resulted in a net decline in ecosystem C and in a release of C to the atmosphere. The future role of Canadian forest ecosystems in the global C budget is subject to ongoing research.

Acknowledgments

This research has been funded, in part, through the ENFOR (ENergy from the FORest) program managed by the Natural Resources Canada, Canadian Forest Service. We thank representatives of Federal and Provincial Agencies, Universities, and Industry Organizations who provided data and information. We thank Sarah Beukema, Tim Webb, Don Robinson, Tamara Lekstrum, and Ralph Mair for assistance in programming, data compilation, model runs, and valuable discussions. We thank Ian Campbell and the anonymous reviewers for comments on the manuscript.

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