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20th century carbon budget of Canadian forests

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ABSTRACT

Our analysis of the carbon budget of Canada's forests (1920–1989) indicates that these forest ecosystems have been a C sink of approximately 0.2 Gt C yr^{-1}. This result challenges the previously-held assumption that forests not directly affected by land use make zero net C contribution to the atmosphere. We attribute our observed C sink to a shift in the forest age-class structure towards a greater average forest age. Forest disturbances, which largely determine Canadian forest dynamics on a time scale of decades, appear to have been less frequent in the period 1920–1970 than in previous decades. They have, however, increased greatly in recent years (1970–1989) and have contributed to a decrease in the C sink. Forests that are subject to large-scale fluctuations in natural disturbance regimes on a time-scale comparable to tree lifetimes do not appear to reach an equilibrium C-exchange with the atmosphere on these time-scales. Assessing C budgets of such forest ecosystems requires an accounting of C dynamics for the entire forest area, not merely for that portion which has recently been affected by anthropogenic disturbances.

1. Introduction

The continued lack of success in closing the global C budget suggests that some assumptions underlying existing estimates of C sources and sinks should be reexamined. Regional and national-scale C budgets can be compiled to analyze C pools and fluxes at spatial and temporal resolutions that are not feasible in global-scale analyses and may be used to examine the assumptions of these larger-scale assessments. Global carbon budgets of terrestrial ecosystems have usually analyzed the C dynamics of only that proportion of the forest area that was directly modified by man's activities (i.e., the area affected by harvesting and land-use) and assumed that the remaining forest area makes a zero net contribution to the global C cycle (e.g., Houghton et al., 1983, 1987). We present data to show that in Canada such anthropogenic disturbances account for only a small proportion of the total forest area which is disturbed annually.

In this study of the carbon budget of the Canadian forest sector, we analyze the C dynamics of both the managed and unmanaged forest areas of Canada and include the effects of both anthropogenic and natural disturbances. We are thus able to assess the previously made assumption that forests not directly modified by man's activities are in steady state. One corollary of this assumption is that the forest age-class structure remains stable over time, i.e., the area of forest in each age-class and the average age of the forests are approximately constant. Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS, Kurz et al., 1992), we have previously shown (Apps and Kurz, 1991) that Canada's forest carbon dynamics are strongly influenced by large-scale stand-replacing disturbances such as wildfire, insect-induced stand mortality and, more recently, harvesting. We have also recently compiled a

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70-year record of both anthropogenic and natural disturbances, such as wildfire and insects, which are known to be affected by climatic conditions, fuel loadings, forest age-class structure and forest protection efforts (Kurz et al., 1994). In this paper we will show how changes in these disturbance regimes (both natural and anthropogenic) have resulted in a shift in the age-class structure and a contemporaneous change in carbon dynamics.

Nearly all forests in Canada are composed of even-aged stands, or of stands dominated by a single age-class (Forestry Canada, 1988). Their age-class structure is described in national forest inventories (Bonnor, 1982, 1985). We use these data, together with the observed record of forest disturbances, in an updated version of the carbon budget model (CBM-CFS2, Kurz and Apps, 1994) to estimate the changes in C content of Canada's forest biomass and soil C pools for the period 1920 to 1989.

2. Methods

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) was used to simulate forest growth, organic matter dynamics, disturbance regimes, and forest regeneration for the 70-year period 1920 to 1989. We have previously used this model and earlier versions of it to examine the contemporary carbon budget of the Canadian forest sector (Apps and Kurz, 1991, 1994) and the sensitivity of Canadian forest systems to potential future changes in disturbance regimes and primary productivity (Kurz and Apps, 1994). Here we use the same model to retrospectively calculate the changes in carbon dynamics associated with the observed record of disturbance, regeneration, and forest growth for the period 1920 to 1989. More details about CBM-CFS2 than are provided here may be found in the cited references.

Our model uses a detailed database of forest conditions derived from the national biomass inventory (Bonnor, 1985). The database is used by stratifying Canada's forests into 457 ecosystem types based on classifiers such as spatial unit, site class, and productivity as described elsewhere (Kurz et al., 1992, Kurz and Apps, 1994). Spatial units are defined by the intersection of the 11 ecoclimatic provinces (EPs) (Ecoregions Working Group, 1989) and the administrative provinces (Apps and Kurz, 1994; Kurz et al., 1992). The CBM-CFS2 simulates forest growth and organic matter dynamics for the 457 ecosystem types (Kurz and Apps, 1994; Kurz et al., 1992). As in previously reported analyses, CBM-CFS2 growth rate estimates were derived from inventory data. In the analysis reported here, we do not explicitly consider the influences of any changes in climate or atmospheric CO_2-concentration on these growth rates over the period of record.

All major C pools and fluxes are simulated by the model (Apps and Kurz, 1994). The biomass C pool includes above- and below-ground forest biomass, but does not account for shrubs, herbs, and mosses. The soil C pool contains all soil organic matter, surface litter, and coarse woody debris. Because we focus on forest ecosystems in the present paper, neither peatland nor forest product C pool dynamics are included in the present analysis. Excluding forest product C pools from the analysis assumes that all harvested C is immediately released to the atmosphere. In reality, some harvested biomass C accumulates in forest product and landfill C pools (Kurz et al., 1992).

Total C (TC) storage in Canadian forests at a year t was calculated by summing over ecosystem types:

$$\mathrm{T}\,C_t = \sum_{i=1}^{457} \sum_{j=1}^{27} \mathrm{Area}_{i,j,t}(\mathrm{Bio}\ C_{i,j,t} + \mathrm{Soil}\ C_{i,j,t}),$$

where i indicates the ecosystem type, j indicates the age-class, $\mathrm{Area}_{i,j,t}$ is the area (ha) in the jth age-class of the ith ecosystem type, and Bio $C_{i,j,t}$ and Soil $C_{i,j,t}$ are, respectively, the biomass and soil C pools (Mg ha^{-1}) in the jth age-class of the ith ecosystem type in year t. In 1920, the model represents Canadian forests as 12,339 records, i.e., 457 ecosystem types each partitioned into 27 age-classes that range from 5 to over 50 years in width.

To initialize the model for the forest conditions in 1920, we had to determine the forest age-class structure in 1920 and to estimate the biomass and soil C content in each of the ecosystem types and age-classes. The age-class structure of Canadian forests is primarily determined by stand-replacing disturbances. It is therefore possible to reconstruct the 1920 age-class structure using the record of stand replacing disturbances for the intervening period together with simple rules that allocate the disturbances to different stand types and ages. These rules are specific for EP and disturbance type. For example, harvesting is applied to forests with high merchantable timber volume, stand-replacing insect outbreaks occur primarily in older softwood forests, and fires burn stands of all ages that contain some minimum amount of biomass.

Canada's national forest biomass inventory provides detailed information on forest conditions throughout Canada in 1980 (Bonnor, 1982, 1985). The average age of records in the inventory is ca. 10 years and we therefore assumed that the inventory represents the forest age-class structure of ca. 1970. Statistics on different forest disturbances in Canada for the period 1920 to present are available from many sources (Kuhnke, 1989; Otvos et al., 1979; Ramsey and Higgins, 1982, 1986; Volney, 1988; Wood and Van Sickle, 1986). We have compiled data on those disturbances which we have previously shown to be significant in determining the annual carbon budget of Canadian forests. Specifically we have constructed a retrospective record of areas annually disturbed by wildfire, insect outbreak, and harvesting (including salvage logging of fire or pest-killed stands) for each of the spatial units that are used in the CBM-CFS. Other disturbances such as windthrow and flooding, which are known to have strong impacts on local carbon budgets, are presently ignored in this national-scale budget because although data are sparse, they are not believed to be significant at this larger scale. Our model does not simulate the effects of forest conversion to agricultural land because such land is not included in the national forest inventory, as is further discussed below.

The age-class structure in 1920 in each spatial unit was inferred from the data using the following iterative procedure. First, a simple model was developed to produce dummy forest age-class structures for each ecoclimatic province for the starting year, 1920, of our carbon budget analysis. The observed record of annual disturbances for the period 1920 to 1969 was then applied to this dummy 1920 age-class structure for each EP, using the rules with which to allocate disturbances to stand types and ages. By applying the known disturbance record from 1920 to 1969, we "predicted" the forest age-class structure in 1970. The "predicted" and the known 1970 age-class structures were compared and the 1920 age-class structures were adjusted where necessary. This iterative procedure was repeated until an acceptable match (in each of the 11 EPs) between the simulated and the observed age-class structure in 1970 was obtained. The resulting non-equilibrium forest age-class structure for 1920 was used to initialize the model.

To initialize conditions of the model further requires the allocation of the 1920 age-class distribution to the different ecosystem types within each spatial unit. To accomplish this, we assumed that the distribution of ecosystem types has not changed over the period 1920–1969 so as to allow the use of the present, known distribution of ecosystem types for the initial conditions of our simulation. Accordingly, we calculated the total area (all age-classes) observed in each ecosystem type in 1970, and distributed this area between age-classes to match the 1920 age-class distribution.

To initialize ecosystem C pools in 1920 we modified the approach reported in earlier works (Kurz et al., 1992; Apps and Kurz, 1994) as follows. The growth, decomposition, and disturbance subroutines of the CBM-CFS2 were used to simulate C dynamics in each of the 457 ecosystem types. The biomass C pool ($Mg\ ha^{-1}$) at a particular age (i.e., the time since last disturbance) of each ecosystem type was calculated directly from the biomass growth functions of that ecosystem type. Soil C pool content ($Mg\ ha^{-1}$) of each ecosystem type was derived from data and simulation. In the CBM-CFS2, the soil carbon pool contains a slow turnover compartment associated with soil organic matter, and three faster turnover pools which include all forest floor detrital material and coarse woody debris. After initializing slow soil C pools with EP-specific soil C data (for details and data sources, see Kurz et al. (1992) and Apps and Kurz (1994)), we simulated the contents of the other pools in each ecosystem type by the following procedure. We first subjected each ecosystem type to two rotations of forest growth, each terminated by wildfire at the average forest age of forests in that ecoclimatic province in 1920. Because in our model, fires transfer biomass C to the soil and detritus pools (while also releasing some biomass and soil C to the atmosphere), this first step is used to simulate initial estimates of the soil and detrital C pools ($Mg\ ha^{-1}$) for

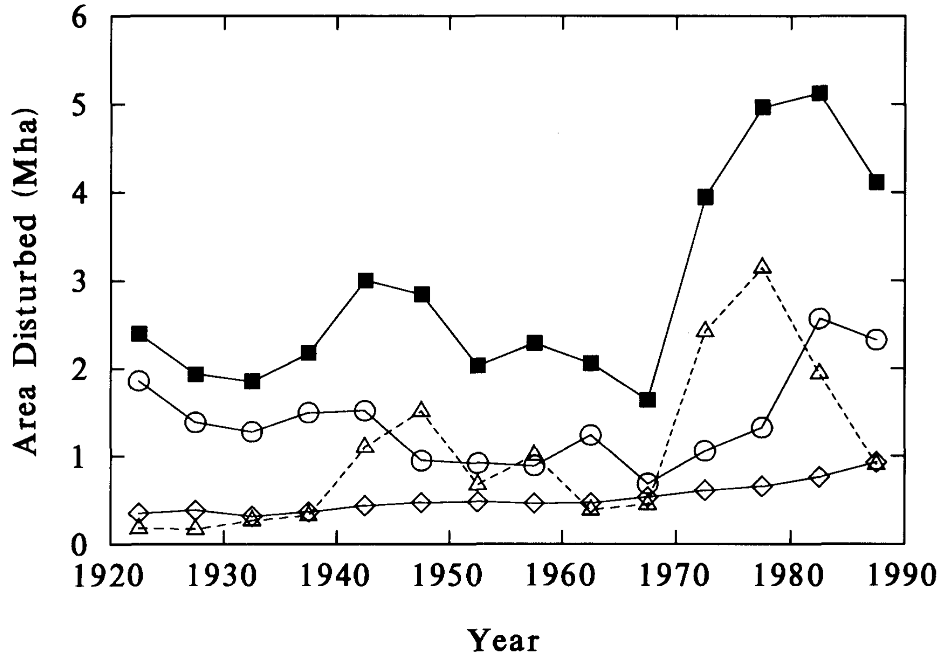

Fig. 1. The average area annually disturbed by forest fires, insect-induced stand mortality and clear-cut logging (including salvage logging of fire or insect killed stands) in the period 1920 to 1989. ■ = total; ○ = fire; △ = insects; ◇ = harvest.

average-aged ecosystem types in each EP. In the CBM-CFS2, the proportion of C affected by each disturbance in each biomass and soil C pool compartment is defined in disturbance- and EP-specific matrices (Kurz et al., 1992). To obtain the values for the soil pool compartments of each ecosystem type in 1920, a third simulated rotation was performed. At the ages corresponding to the mid-points of each of the 27 age-classes, the average simulated biomass and soil C density for each age-class and ecosystem type were assigned to the initial state records. Using the equation given above, total C storage in 1920 was calculated. The CBM-CFS2 was then used to simulate ecosystem C dynamics from 1920 to 1989.

3. Results

The total forest area included in this analysis is 404.2 Mha. Fig. 1 summarizes data on the average area annually disturbed for each of the seven decades included in this analysis. At the national scale, fires and insect-induced stand mortality are the dominant disturbance types, but there are large regional differences that are represented in the model. The data also show that there was little change in the total area disturbed from 1920 to 1969 followed by a large increase in the last two decades. We note also that even in the 1980s, when harvest levels were highest, on average only 0.2% of the total forest area was affected by clearcut logging.

We find that there was a net ecosystem C accumulation of 14.4 Gt over the 70-year period, representing an average annual accumulation of 0.2 Gt C (Table 1). We also report that our simulations show significant fluctuations throughout the 70-year period and will discuss these else-

Table 1. *Summary of average age, biomass, soil, and total ecosystem C for Canadian forests in 1920, 1970, and 1990*

Year	Average age (years)	Biomass (Gt)	Soil (Gt)	Ecosystem (Gt)
1920	59.0	11.0	59.9	70.8
1970	81.2	16.4	67.5	84.0
1990	78.3	14.5	70.6	85.2
Change	19.3	3.5	10.7	14.4

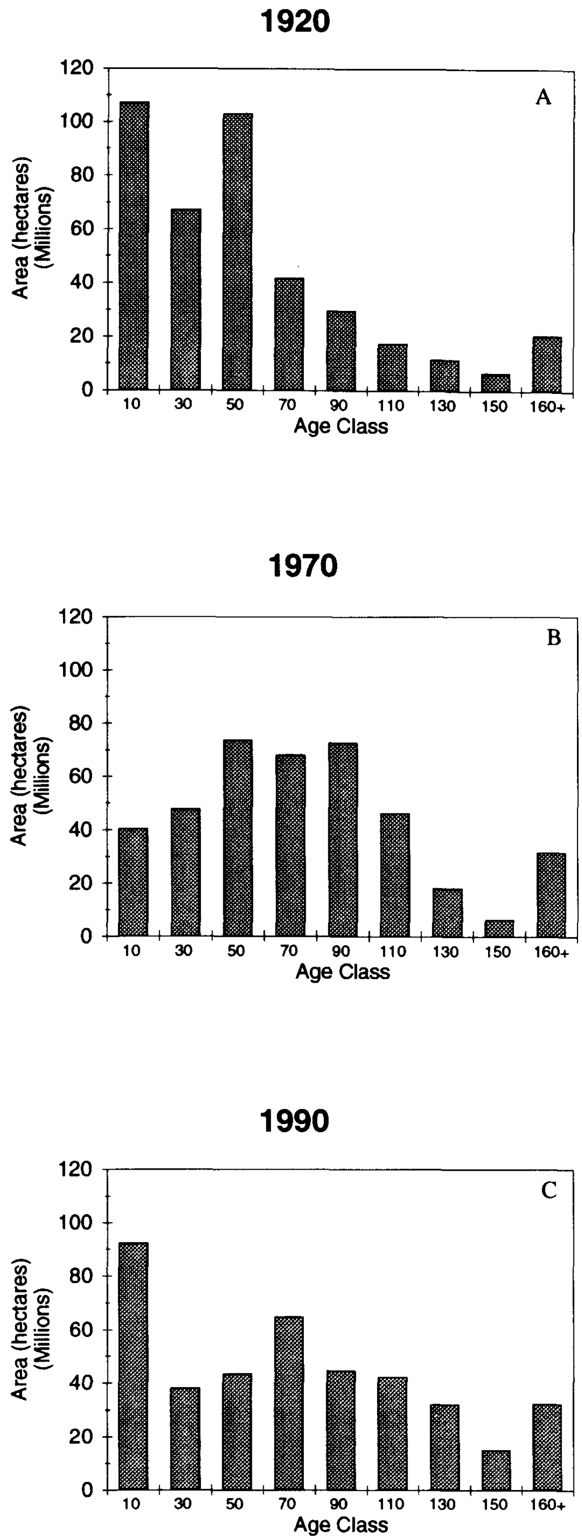

Fig. 2. The general trend towards older ages in Canada's forest age-class distributions of 1920, 1970, and 1990. Histogram shows 20-year age-classes.

where. Both biomass and the soil-detritus pools contributed to this net ecosystem C uptake (Table 1). We observed a biomass C pool increase of 3.5 Gt C over the period and average increase of forest age of 19 years (Table 1). The age increase provides insight to explain the observed C increase: older forests generally contain more forest biomass. Average age and biomass C were found to decrease slightly during the last 20 years of the period. The model results indicate that the decrease in biomass is due partly to stand breakup and biomass decline in overmature forest stands as well as to the large increase in the area subjected to annual disturbance. Over the 70-year period, we also estimate the soil and detritus C pools to have increased by 10.7 Gt C. We associate this with litter and coarse woody debris accumulation in older forests that have been less frequently disturbed by fire.

Our reconstruction of the forest age-class distribution for 1920 (Fig. 2a) shows that 68.5% of the forest area was found in the youngest three age-classes (i.e., younger than age 60 years), suggesting that periods of intensive disturbances had occurred prior to 1920. By 1970, only 40.0% of the area remained in the youngest three age-classes (Fig. 2b). Moreover, the 1970 forest age-class distribution contains significantly less area in the youngest two age-classes than in the next three (i.e., 40 to 99 year) age-classes. We interpret the smaller area in the youngest age-classes as the result of a reduction in forest disturbances (Kurz and Apps, 1993). The substantial increase in forest disturbances in the period 1970–1989 resulted in a corresponding increase in the area of the youngest forest age-class in the simulated age-class structure for 1990 as shown in Fig. 2c. Although Canada's 1991 National Forest Inventory has not yet been published, available provincial data confirm an increase in forest area in the youngest forest age-class for this period (Ontario Ministry of Natural Resources, 1992).

4. Discussion

Previous studies of the contribution of Canadian forests to the global C cycle concluded that these forests were a small net C source based on an analysis of C dynamics of areas directly affected by land use and harvesting and the assumption that all other areas make a zero net contribution to the C budget (Houghton et al., 1987). Our study, which considers the C dynamics of natural and managed forests, shows that this assumption is invalid for Canada, at least during the period from 1920 to 1989. We find that forest land not directly affected by land-use change and forestry practises has not been in steady state (i.e., net zero C exchange with the atmosphere) and has rather been a net atmospheric C sink for most of the 70-year period. Large-scale and long-term (decades and longer) fluctuations in forest disturbance regimes have caused a shift in the forest age-class structure towards a greater average forest age.

At present, the reasons for the changes in the area annually disturbed during the 20th century are uncertain and require further documentation, which we are assembling. We can, however, ask the question: has direct human activity, through changes in harvesting and forest protection policies, been a significant factor at a national scale? The area annually affected by harvesting has increased over the period of record and therefore has certainly contributed to the overall trend in disturbed area. At a national scale, however, the trend is dominated by changes in natural disturbances. These trends do not apply uniformly at smaller scales: the significant variation in the disturbance record over time within different EPs is beyond the scope of this paper. Forest fire suppression in Canada started on a very limited scale in the 1920s in response to wide-spread fires that had been reported throughout the country. In recognition of their ecological importance and for economic considerations, fires are allowed to burn freely in Canada's sparsely populated northern regions (Stocks and Simard, 1993). Fire suppression may have contributed to reduced disturbances in the period 1920–1969, but wildfires in northern regions with limited suppression increased greatly in the 1980s, which was the warmest decade in Canada's 100-year temperature record (Gullett and Skinner, 1992). At present, it does not appear that direct human activity has been the major reason for the observed changes in disturbance regimes of Canada's forests.

We emphasize that in the analysis presented here, we have focused only on the forest ecosystems and have accounted for removals of biomass C by harvesting but not for storage in forest product pools. Accounting for the fate of wood products in use and in landfills further increases C storage (Kurz et al., 1992).

Our analysis does not account for the conversion of forests to agricultural land but we argue that this results in only a small error and does not significantly alter our conclusions. In 1920, Canada contained 28.7 Mha of improved agricultural land (McCuaig and Manning, 1982, and the series of publications for each Province e.g., Statistics Canada 1992) which increased to 45.6 Mha by 1990. The net increase of the area of improved agricultural land was 16.9 Mha, this representing the upper bound of forest conversion to agriculture. From 1920–1990, the net increase in improved agricultural land in the prairie provinces (Alberta, Manitoba, and Saskatchewan) was 20.3 Mha. Most of this land, however, was derived from grassland ecosystems and not from forests and will therefore not affect the forest ecosystem C budget. In central and eastern Canada, the area of improved agricultural land declined over the period, though only a portion of this will have reverted back to forest land.

Our results are only slightly sensitive to the uncertainties in the initial conditions selected for 1920. Given that the 1970 age-class structure in the national forest inventory and the recorded disturbance statistics are based on data, the uncertainty in the initial age-class structure is primarily in the rules we use to allocate disturbances to forest types and stand ages. Although alternative rules can be formulated, there is little latitude for changes: clearcut logging does not occur in low volume or young forests; stand-replacing insects such as mountain pine beetle and spruce budworm do not attack primarily young stands or hardwood forests, and the large wildfires that dominate the fire statistics do not selectively burn stands in particular age classes. We have, however, explored a set of alternative rules in which fires preferentially affect older stands. Although this change affected the initial conditions, as expected, it altered neither the pattern of C dynamics over the 70 year period nor the conclusions about increased average forest age and non-steady state conditions.

Can the terrestrial C sink that we have identified in this study be sustained? We think not: the mechanism we identify in our analysis is associated with an increase in the average age of forests. Boreal forests, however, can not age indefinitely: as they pass through maturity, net biomass growth rates decrease, fuel accumulates, and the susceptibility to insect attack increases. In fact, in the past 20 years, net forest growth has decreased and disturbances have increased (Kurz and Apps, unpublished data), and we speculate that this may indicate boreal ecosystem ecological feedbacks which operate to limit further increase in average forest age.

Kauppi et al. (1992) found that Scandinavian forests are also currently a C sink, but their study suggested that changes in forest growth rates due to nutrient import associated with air pollution are the primary mechanism responsible for the increase in ecosystem C storage. Our present analysis focused on structural changes in Canada's forests: changes in ecosystem C dynamics in response to rising CO_2 levels, changed temperature regimes or air pollution were not considered. These and other factors could further affect the carbon exchange with the atmosphere, possibly in synchrony with the mechanism we identify in this work.

The terrestrial C sink mechanism we have presented here for Canadian forests may also operate in other forest biomes whose dynamics are dominated by disturbances. If large-scale and long-term shifts in forest disturbance regimes occur in those regions, C storage and net exchange with the atmosphere will also be affected. Future research should address the impact of changes in disturbance regime on forest age-class structures in other boreal forest regions to determine to what extent this might explain a component of the global missing C sink.

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