GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 14, NO. 3, PAGES 839-849, SEPTEMBER 2000

Annual carbon balance of Canada's forests during 1895-1996

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Abstract. This paper reports annual carbon (C) balance of Canada's forests during 1895-1996 estimated using the Integrated Terrestrial Ecosystem C-budget model (InTEC) [*Chen et al.*, this issue]. During 1895-1910, Canada's forests were small sources of 30±15 Tg C yr^{-1} due to large disturbances (forest fire, insect-induced mortality, and harvest) in late nineteenth century. The forests became large sinks of 170±85 Tg C yr^{-1} during 1930-1970, owing to forest regrowth in previously disturbed areas and growth stimulation by nondisturbance factors such as climate, atmospheric CO_2 concentration, and N deposition. In recent decades (1980-1996), Canada's forests have been moderate sinks of 50±25 Tg C yr^{-1}, as a result of a tradeoff between the negative effects of increased disturbances and positive effects of nondisturbance factors. The nondisturbance factors, in order of importance, are (1) atmospheric N deposition (measured by a national monitoring network), (2) net N mineralization and fixation (estimated from temperature and precipitation records), (3) growing season length increase (estimated from spring air temperature records), and (4) CO_2 fertilization (estimated from CO_2 records using a leaf-level photosynthesis model). The magnitudes of modeled nondisturbance effects are consistent with simulation results by the Carnegie-Ames-Stanford Approach (CASA) and are also in broad agreement with flux measurements above mature forest stands at several locations in Canada. Results for the disturbance effects agree with a previous study [*Kurz and Apps,* 1996]. The overall C balance from InTEC generally agrees with that derived from tree ring data [*Auclair and Bedford*, 1997] and from forest inventories. The combination of our result and that of *Houghton et al.* [1999] for the United States suggests that North America (> 15°N) was probably a C sink of 0.2-0.5 Pg C yr^{-1} during 1980s, much less than that of 1.7 Pg C yr^{-1} estimated by *Fan et al.* [1998] using an atmospheric inversion method.

1. Introduction

Regional terrestrial C balance is an important aspect of the global C cycle, which is presently of considerable interest in global change studies. Models for evaluating terrestrial C balance usually involve C pools that store C, C fluxes that transfer C between pools, and factors that affect C fluxes and consequently sizes of C pools. Various factors, such as climate variability, atmospheric CO_2 concentration, N deposition, forest fire, harvesting, insects, and land use changes have been found to be important for C cycle [*Fung*, 1996; *Greenough et al.*, 2000]. Many studies have dealt with the individual effects of these factors, for example, CO_2 fertilization [*Bazzaz*, 1990], climate variability [*Dai* and *Fung*, 1993], N deposition [*Townsend et al.*, 1996], land use change [*Houghton*, 1995], natural and anthropogenic disturbances [*Kurz* and *Apps*, 1996]. Because the forest C balance is affected by all these effects, the results can be biased when some of these factors are not considered or the interactions among them are not fully accounted for [*Greenough et al.*, 2000]. Therefore the need for a comprehensive analysis cannot be overemphasized [*Fung*, 1996]. Considerable progress has been made in this direction. For example, *Cao and Woodward* [1998] studied the effects of climate variability and CO_2 fertilization on C balance, while *Rastetter et al.* [1997], *McGuire et al.* [1992], and *Melillo et al.* [1993] integrated the effects of changes in CO_2, climate, and N deposition. In this study, we further integrate the effect of disturbance factor (i.e., forest fire, insect-induced mortality, and harvest) and nondisturbance factors (i.e., CO_2, climate, and N deposition) into a regional Integrated Terrestrial Ecosystem C-budget model (InTEC) (Figure 1, see details given by *Chen et al.* [this issue].

The net terrestrial C exchange is a small difference between the large terms of C gain (net primary productivity (NPP)) and C loss (heterotrophic respiration and C release through disturbances). As these terms can only be measured or estimated to certain accuracy, the resulting error can easily be several times larger than the difference sought. For example, NPP can at best be estimated to an accuracy of ~75% [*Liu et al.*, 1997], but the global terrestrial sink is only

Paper number 1999GB001207.
0886-6236/00/1999GB001207$12.00

2-3% of the global NPP [*Houghton et al.*, 1996]. To avoid this problem, InTEC uses a historical change approach. It assumes that the C and N exchanges between terrestrial ecosystems and the atmosphere were in equilibrium under the mean climate conditions, mean N deposition rate, and mean disturbance rates during the preindustrial period. This assumption means that in any given year the terrestrial ecosystem could be either a sink or source due to year-to-year changes in disturbance and climate conditions, yet when averaged over centuries before the recent global warming and CO_2 concentration increase, the C-N cycles would be in equilibrium state. During the industrial period the C balance is estimated as the sum of changes in all component fluxes for individual years. The core of InTEC is a mechanistic integration of Farquhar's biochemical model of leaf photosynthesis [*Farquhar et al.*, 1980; *Bonan*, 1995; *Luo et al.*, 1996] with Century soil C/N cycling model [*Parton et al.*, 1987; *Schimel et al.*, 1994; *Townsend et al.*, 1996]. The integration is implemented through new temporal and spatial scaling algorithms.

In this paper, we report estimates of the C balance of Canada's forests during 1895-1996 by using the InTEC model and by treating the entire forest area as one entity. Data sources and the processing methodology are given in section 2, followed by results in section 3 and discussion in section 4, in which we partition the effects of disturbance and nondisturbance factors on the C balance into different components. The results are compared with estimates previously made by other researchers using independent methods.

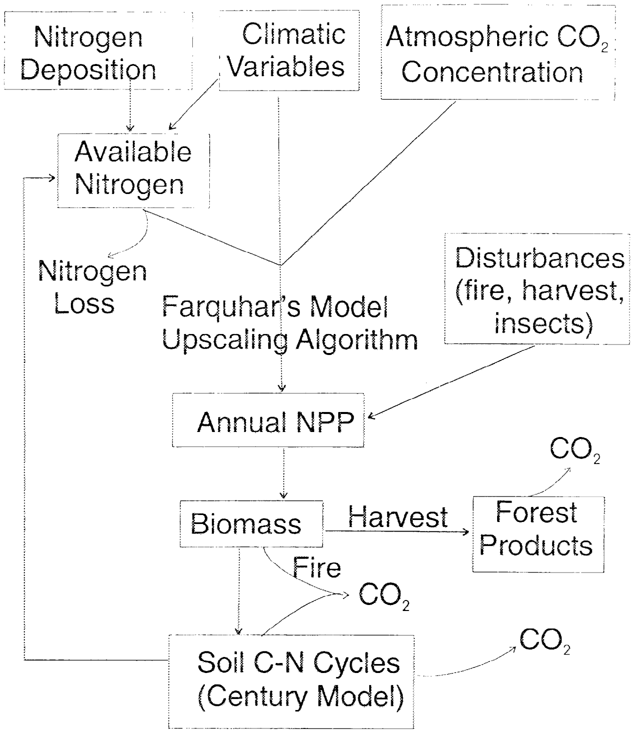

Figure 1. Structure of an integrated terrestrial ecosystem C budget model (InTEC) which synthesizes the interactive and long-term effects of disturbances, N deposition, climate change, and atmospheric CO_2 concentration increase on the C balance of forests. Dashed arrows represent influences, whereas solid arrows show direct C and N flows.

2. Data Sources and Processing Methods

2.1. Disturbance and Regrowth

Statistics of the annual burned forest area in Canada from 1930 to 1996 are taken from *Weber and Flannigan* [1997], and statistics of harvested area during 1970-1996 and insect-infected area during 1977-1996 are from Canadian National Forestry Database Program (available on the World Wide Web at http://www.nrcan.gc.ca/cfs). These disturbed area data were extended back to 1920 using the 5-year average during 1920-1989 [*Kurz et al.*, 1995]. Areas disturbed by fires and insects prior to 1920 were inferred from the age class distribution in 1920 [*Kurz et al.*, 1995], using the Weibull distribution:

$$A(y,i) = A_t \frac{q(i)}{\varphi(1/s+1)} e^{-[q(i)y]^s}, \qquad (1)$$

where $A(y,i)$ is the forest area at age y in year i, A_t is total forest area, q is the total fire and insect occurrence frequency, φ is the gamma function, and s is the shape parameter with an assumed value of 1.5 [*Kasischke et al.*, 1995]. Since the inferred values are total disturbed area, we need to partition it into area affected by fire, insect-induced mortality, and harvest. The partition into fire and insect-affected areas was based on the mean ratio found in 1920-1996, while assuming the annual harvested area before 1920 to be the same as that in 1920 because of the paucity of direct data. Figure 2 shows the histogram of the total disturbed area for Canada and its components from 1760 to 1996. The natural regeneration period for Canada's forests, i.e., the average length of time it takes to regenerate after disturbance without human intervention, ranges from 1 to 10 years, with a mean of ~5 years [*Bunce*, 1989]. We used 5 years as the natural regeneration period in this study, 0 years for directly seeding, and –4 years for planting with seedling of age 3-5 years. The area data of seed and seedling plantation are taken from the Canadian National Forestry Database Program (available on the World Wide Web at http://www.nrcan.gc.ca/cfs).

2.2. Nitrogen Deposition, Fixation, and Net Mineralization

Table 1 provides the average N deposition rate on Canada's forests during 1983-1994 from measurements made by Canadian Air and Precipitation Monitoring Network (CAPMoN) [*Ro et al.*, 1995]. By 1990, CAPMoN operated 30 sites across the country. Many of these sites are located in forested areas and therefore are ideal for the determination of N deposition in Canada's forests. Wet deposition rates of NO_x and NH_4^+ measured at these sites [*Ro et al.*, 1995] were used to estimate the average provincial rates. Dry deposition and droplet deposition rates (i.e., cloud impact on elevated terrain and fog on nonmountain terrain) were estimated following *Shannon and Sisterson* [1992]. Since 1983, the N deposition rates have been stable in Canada [*Ro et al.*, 1995]. Therefore an average rate is used for the period from 1983 to 1996, while the rate before 1983 was extrapolated

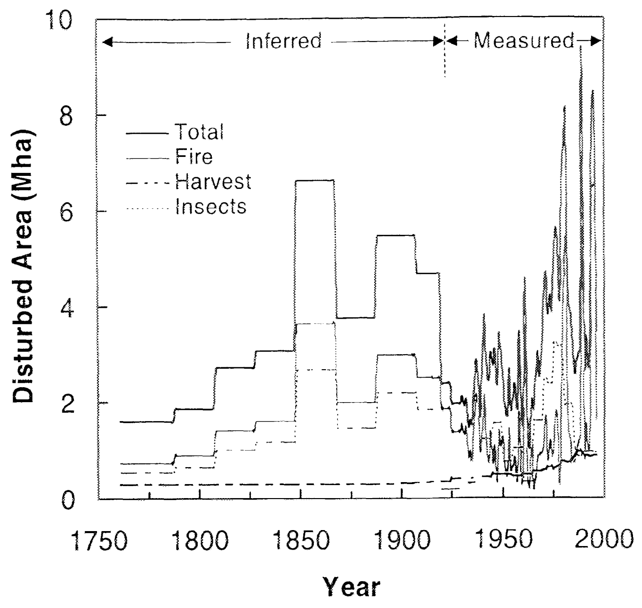

Figure 2. Areas of Canada's forests disturbed by forest fire, harvest, and insects during the period from 1760 to 1996. Measurements were available from 1920, and values before 1920 were inferred from age-class distribution in 1920 [*Kurz et al.*, 1995].

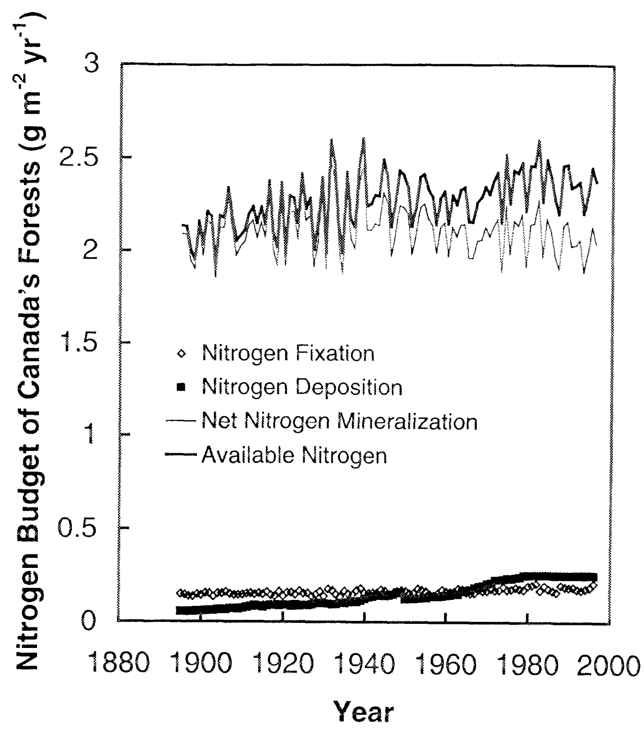

Figure 3. Average rates of N deposition on Canada's forests from 1895 to 1996. Also shown are N fixation and net mineralization rates. N deposition was measured in 1983-1996 and was extended to 1895 on the base of the trend of national greenhouse gas emission records, which have a discontinuity at 1948.

proportionally to Canada's greenhouse gas emission. The total deposition rate was then calculated by multiplying these rates by the provincial forest areas in the 1991 (Statistics Canada, available on the World Wide Web at http://www.statcan.ca). Between 1895 and 1996, N deposition increased from 0.05 to 0.25 g N m^{-2} yr^{-1} (Figure 3). Also plotted in Figure 3 are the net N mineralization and N fixation rates for the same period, calculated from temperature and precipitation records using the methods described by *Chen et al.* [this issue]. Net N mineralization fluctuated around 2 g N m^{-2} yr^{-1}, with a small increasing trend from 1895 to 1940 followed by a small decreasing trend from 1940 to 1996. This simulated result appears to be somewhat low compared to observations of *Nadelhoffer et al.* [1992] who measured net N mineralization ranging from 1.53 to 5.12 g N m^{-2} yr^{-1} for North American boreal forests. The N fixation rate, which is based largely on the work of *Chapin* and *Bledsoe* [1992], increased gradually from ~0.14 in 1985 to ~0.18 g N m^{-2} yr^{-1}

Table 1. N Deposition on Canada's Forests, Tabled by Province and Deposition Process

Province or Territory	NO_x Wet	NO_x Dry	NO_x Droplet	H_4N^- Wet	H_4N^- Dry	Sum per Unit Area	Sum per Province
New Brunswick	1.9	0.69	0.16	1.37	0.36	4.48	27.4
New Foundland	0.7	0.25	0.09	0.51	0.13	1.68	37.8
Nova Scotia	2.2	0.8	0.13	1.59	0.41	5.13	20.1
Ontario	1.96	0.71	0.08	1.41	0.37	4.53	262.9
Prince Idward Island	1.5	0.55	0	1.08	0.28	3.41	1
Quebec	2.24	0.82	0.11	1.62	0.42	5.21	437.5
Alberta	0.3	0.22	0.03	0.28	0.15	0.97	37.1
British Columbia	0.5	0.18	0.06	0.47	0.12	1.33	80.6
Manitoba	0.6	0.44	0.06	0.72	0.38	2.2	57.7
Saskatchewan	0.4	0.29	0.03	0.38	0.2	1.3	37.3
Northwest Territories	0.15	0.11	0.11	0.18	0.09	0.65	39.7
Yukon	0.15	0.11	0.11	0.18	0.09	0.65	17.8

The unit is kg N ha^{-1} yr^{-1} except for the sum per province which is Kt N y^{-1}. The total is calculated as the product of forest area and overall N deposition rate.

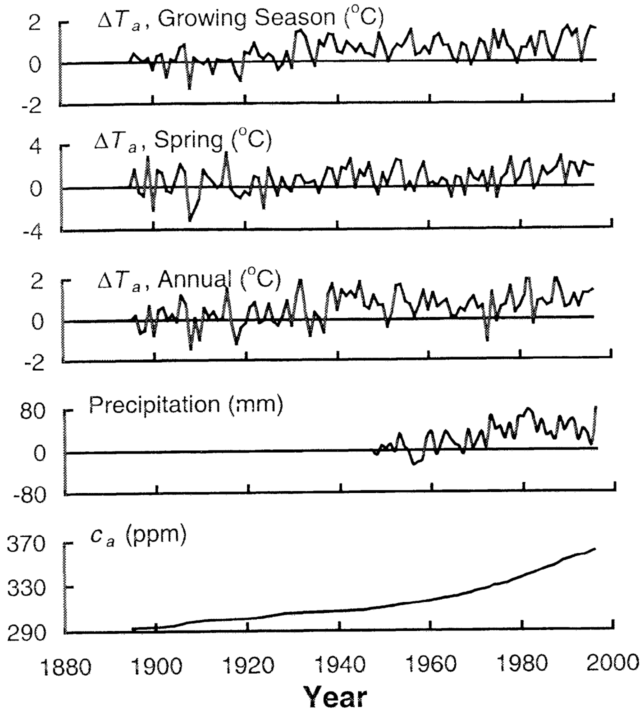

Figure 4. Growing season mean air temperature, spring (March-May) mean air temperature, annual mean air temperature, and annual cumulative precipitation shown as departure from pre-1895 levels. Also shown is the annual mean atmospheric CO_2 concentration from 1895 to 1996.

in 1996 as temperature and precipitation increased. The net N mineralization is the largest component of available N for plants in forest ecosystems [*Aber* and *Driscoll*, 1997].

2.3. Climate, Atmospheric CO_2 Concentration, and Other Variables

Figure 4 shows anomalies of national mean growing season and spring (March-May) air temperatures during 1895-1996 relative to pre-1895 levels. The data sources are Atmospheric Environment Services, Environment Canada [*Gullett and Skinner*, 1992] (see also Climate Trends and Variations Bulletin for Canada, available on the World Wide Web at http://www.tor.ec.gc.ca/ccrm/) and Global Historical Climatology Network [*Peterson and Vose*, 1997]. Prior to 1895, the values are assumed to be constants (linearly extrapolated to the year 1894 from data during 1895-1996). Soil temperatures were estimated by keeping the linear trend of annual mean air temperature but dampening its interannual amplitude by 30% on the basis of simultaneous air and soil temperature measurements at Boreal Ecosystem-Atmosphere Study (BOREAS) sites [*Goulden et al.*, 1998; W. J. *Chen et al.*, 1999]. National annual precipitation data are available after 1947 [*Gullett and Skinner*, 1992; Climate Trends and Variations Bulletin for Canada]. We assumed that precipitation before 1947 was equal to the value at 1947 (Figure 4).

Atmospheric CO_2 concentration data are taken from the Siple Station ice core for the period from 1895 to 1957 [*Neftel et al.*, 1994] and from Mauna Loa, Hawaii, for the period from 1958 to 1996 [*Keeling and Whorf*, 1996], available at WWW site: http://cdiac.esd.ornl.gov/trends/co2. The average NPP of Canada's forests in 1994 of 267 g C m^{-2} yr^{-1} was obtained using the Boreal Ecosystems Productivity Simulator (BEPS) [*Liu et al.*, 1997; J.M. *Chen et al.* 1999], based on land cover and leaf area index maps derived from 1 km × 1 km advanced very high resolution radiometer (AVHRR) data in 10-day intervals, soil texture, and daily meteorological data. This NPP estimate is consistent with recent measurements compiled by *Gower et al.* [1997], who reported NPP for boreal evergreen forests ranges from 175 to 430 g C m^{-2} yr^{-1}, with an average of 273 g C m^{-2} yr^{-1}.

3. Results

3.1. NPP of Canada's Forests From 1895 to 1996

If the disturbance rates had remained at the preindustrial levels but the nondisturbance factors (i.e., N deposition, atmospheric CO_2, and climate change) changed as they did, the average NPP of Canada's forests in the recent 2 decades (1980-1996) would have increased 67 g C m^{-2} yr^{-1}, or 32%, over that in 1895 (Figure 5). N deposition, climate change, and CO_2 fertilization would have contributed 11.6%, 16.6%, and 2.9%, respectively, to the 32% increase in NPP, with the remaining 1.3% resulting from interactions among them. These partitions are made by changing only the factor

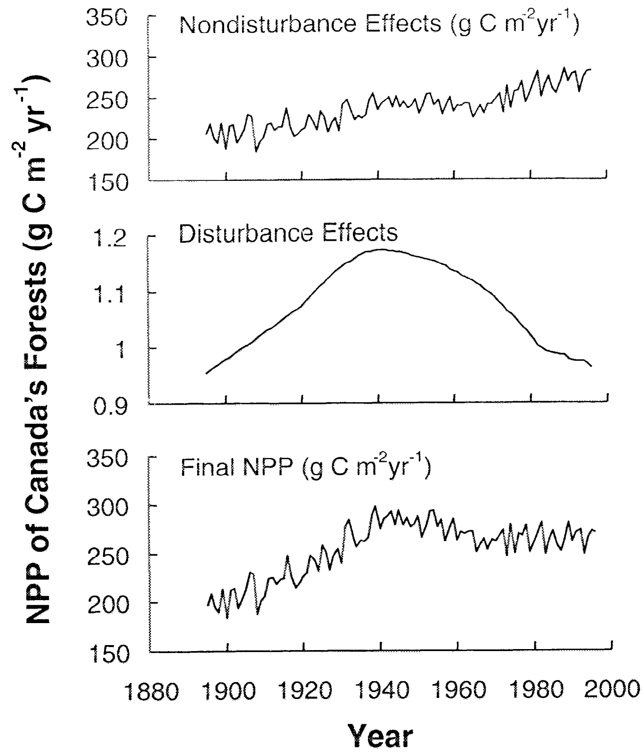

Figure 5. Annual NPP of Canada's forests affected by nondisturbance factors (e.g., N deposition, climate change, and CO_2 fertilization) from 1895 to 1996. The effects of disturbances are shown as a dimensionless multiplier, with a value of 1 at the average disturbance rate.

concerned while keeping all other factors at the preindustrial levels. The N use efficiency in undisturbed forests ranged from 80 to 110 g C of NPP per gram N available for the last century, similar to the finding of *McGuire et al.* [1992]. The β factor for the CO_2 enrichment effect on NPP [*Friedlingstein et al.*, 1995] was 0.14 during 1895-1996. This value is much smaller than the 0.61 of *Friedlingstein et al.* [1995], who calculated the β value by attributing all missing C sink to CO_2 enhancement for the period of 1850-1990.

The high disturbance rate from late half of the last century to the beginning of this century resulted in a larger fraction of less productive forest land than would be expected under an average disturbance regime, resulting in a lower NPP during the periods from 1895 to 1920 than the later period from 1930 to 1970 (Figure 5). From 1930 to 1970, the disturbance rates were lower than average, and the previously disturbed areas entered into productive ages, both effects producing a higher total NPP than would be with constant disturbance rates. The increase in disturbances during recent decades reversed the increasing trend.

After integrating the effects of disturbance and nondisturbance factors, we found a rapid increase in the annual mean NPP of Canada's forests during the period 1895-1940 (Figure 5). Subsequently, NPP decreased slightly because of the dominating role of disturbance factors despite the growth increase caused by N deposition, climate warming, and CO_2 fertilization.

3.2. Carbon Release From Canada's Forests During 1895-1996

The total heterotrophic C release from Canada's forests includes heterotrophic respiration in soil, forest product oxidation, and C emission due to fire. Among the three C release processes, soil heterotrophic respiration was an order of magnitude larger than the others during 1895-1996 (Figure 6). As shown in Figure 6, the soil heterotrophic respiration increased quickly from ~800 to ~950 Tg C yr^{-1} during 1895-1940 because of the increases in soil decomposition rate as a result of increasing temperature and in soil C stock from increasing NPP. This respiration increase slowed since 1940, mainly because of the small increase in the C input from plants to soil as NPP fluctuated approximately at the same level but also because of the slight decrease in temperature during 1940-1970. During the decade of 1990s the mean annual soil heterotrophic respiration was ~1000 Tg C yr^{-1}.

The forest product oxidation rate increased steadily from ~14 to ~25 Tg C yr^{-1} during 1895-1996 (Figure 6), as a result of an increase in area harvested in Canada. The annual C emission due to fire was lowest at ~ 15 Tg C yr^{-1} during the low fire period of 1920-1970 (Figure 6). During the recent decades since 1980, the annual C emissions due to fire were more than doubled, with an average of 36 Tg C yr^{-1} for this period. The interannual variation was substantial during this period, ranging from 10 to 102 Tg C yr^{-1}. Using spatially explicit C density data and observed fraction of C consumed during fires, *French et al.* [1999] estimated that the annual C emission due to fire in the North American boreal forest region ranged from 7 to 124 Tg C yr^{-1} during 1980-1994. Our results are in reasonable agreement with this estimate, although for an individual year the uncertainty could be as large as 50% [*Chen et al*, this issue].

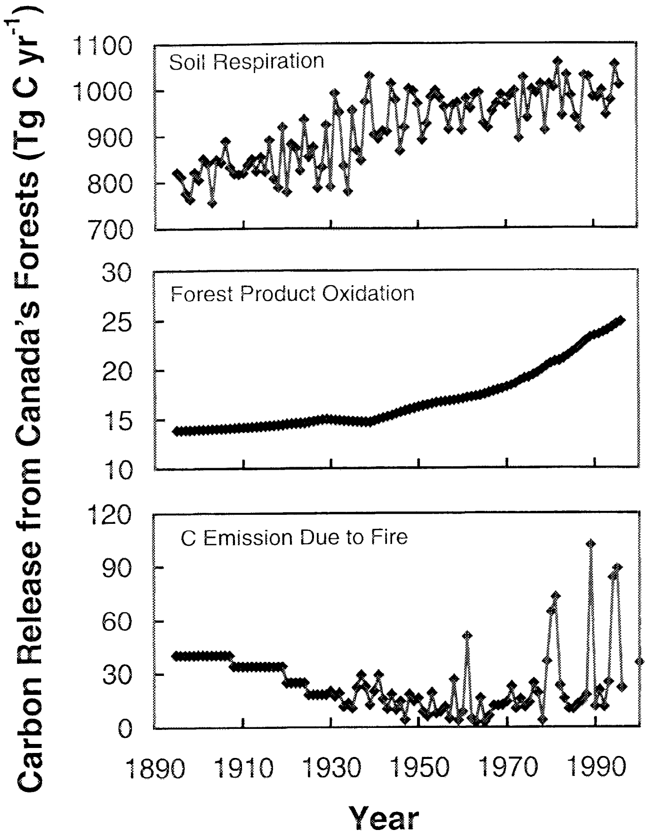

Figure 6. Annual carbon release from Canada's forests due to soil respiration, forest product oxidation, and C emission due to fire during 1895-1996. Note the difference in the scale of y axis.

3.3. Carbon Balance of Canada's Forests During 1895-1996

The positive effects of nondisturbance factors have increased the C balance of Canada's forests substantially during 1895-1996 (Figure 7). N deposition and CO_2 fertilization were characterized by gradual increase, with interannual variations much smaller than those of climate effects. Consequently, interannual variations in the C balance of Canada's forests have been dominated by climate variability, whereas over the long term the effects of N deposition and CO_2 fertilization have accumulated to become substantial. During 1895-1996, N deposition was the largest contributor to the nondisturbance effects with a total contribution of ~42%, followed by climate change at ~34% and CO_2 fertilization at ~19% (Table 2).

The high disturbance rates in late nineteenth century caused Canada's forests to release C by ~30 Tg C yr^{-1} (Figure 7). During 1930-1970 the low disturbance rates, in combination with forest regrowth in areas disturbed in late nineteenth century, allowed Canada's forests to uptake C by ~100 Tg C yr^{-1}. The increased disturbances during 1980-1996 released 60 Tg C yr^{-1} from Canada's forests.

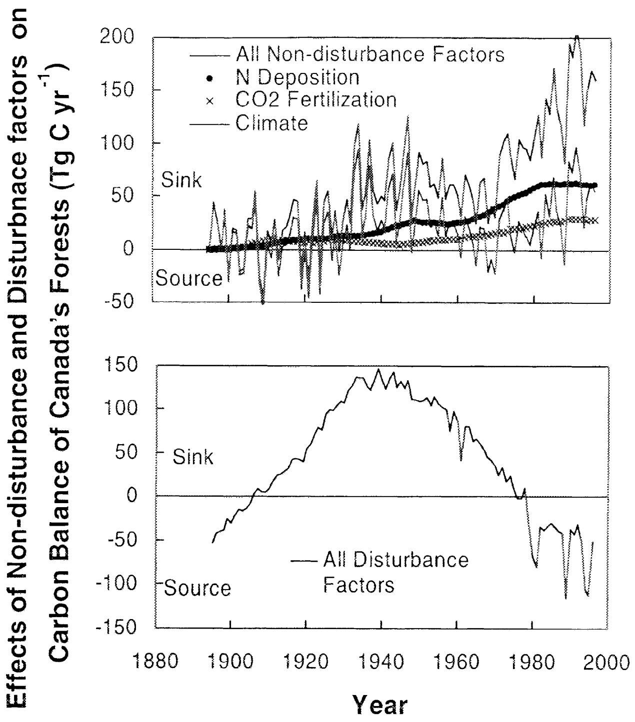

Figure 7. Partitioning the effects of nondisturbance and disturbance factors on C balance of Canada's forests from 1895 to 1996.

Averaged over 1895-1996, ~64% of the ~100 Tg C yr^{-1} sequestered by Canada's forests in this century can be attributed to nondisturbance factors and ~43% can be contributed to disturbances (Table 2). The interaction between nondisturbance and disturbance factors reduced sequestration by ~7%. In recent decades (1980-1996), nondisturbance factors affected the C balance with percentages similar to those during 1895-1996, but the magnitudes of these effects were approximately doubled (Table 2).

After integrating the effects of all the above factors, we estimated that Canada's forests, which includes forest product C pools, were a source of carbon with a magnitude of 30±15 Tg C yr^{-1} from 1895 to 1905 (Figure 8). The uncertainty in the C balance of Canada's forests is ~50%, based on sensitivity analysis by *Chen et al.* [this issue]. The forest became a sink afterward and maintained at high levels of 170±85 Tg C yr^{-1} during 1930-1970 mainly owing to forest regrowth and partly owing to nondisturbance factors. Starting from 1970, the regrowth advantage diminished as the areas disturbed in late nineteenth century became "old" forests. In the meantime, disturbances increased, resulting in a substantial reduction of the C sink. However, because of the positive effects of N deposition, climate warming, and CO_2 fertilization, Canada's forests remained a sink of 50±25 Tg C yr^{-1} during 1980-1996 (Table 2). This C sink is ~34% of the Canada's greenhouse gas emission of 155.3 Tg C yr^{-1} by fossil fuel combustion during 1980-1996. Averaged over the whole period from 1895 to 1996, Canada's forests sequestered ~100 Tg C yr^{-1}, compared to 74 Tg C yr^{-1} greenhouse gas emission.

4. Discussion

4.1. Effects of Nondisturbance Factors Compared With Other Simulations and Flux Measurements

Using the Carnegie-Ames-Stanford approach (CASA), *Potter and Klooster* [1999] estimated that the net ecosystem productivity (NEP) of Canada's ecosystems was 100 and 170 Tg C yr^{-1} in 1987 and 1988, respectively. These NEP values were simulated at 1° resolution but did not include the effects of disturbance factors. In the same years the C balance estimated in this study for nondisturbed forests was 161 and 109 Tg C yr^{-1}, respectively, agreeing well with the CASA simulation results.

The result of Canada's forests that were not disturbed in recent decades being a small sink is also supported by flux measurements made using the eddy covariance technique over forest stands in Canada. *Goulden et al.* [1998] reported an annual NEP ranging from –70±50 (i.e., a source) to 10±50 g C m^{-2} y^{-1} (i.e., a sink), with a mean of -30±50 g C m^{-2} yr^{-1} from 1994 to 1997 at an old black spruce stand (NOBS) in the northern BOREAS study area. A sink of 200±30 g C m^{-2} yr^{-1} in 1994 and 130±30 g C m^{-2} yr^{-1} in 1996 at an old aspen stand

Table 2. Effects of Nondisturbance Factors and Disturbances on NPP and C Balance of Canada's Forests in This Century (1895-1996) and the Recent Decades (1980-1996)

	ΔNPP 1895-1996	C Balance 1895-1996	ΔNPP 1980-1996	C Balance 1980-1996
Nitrogen deposition	9.5	6.1 (25.6)	24	14.7 (61.3)
Climate Change	17.1	5 (21)	34.2	10.7 (44.8)
CO_2 fertilization	2.7	2.9 (11.9)	6.1	6.5 (27.2)
All nondisturbance factors	30.1	14.8 (61.7)	66.9	34.7 (145)
All disturbance factors	15.6	10 (41.5)	-2.8	-13.3 (-55.5)
Integrated effects	47.9	23.1 (96.4)	63.1	12.7 (53)

Nondisturbance factors are N deposition, CO_2 fertilization, and climate change (which includes changes in growing season climatic conditions, growing season length, net N mineralization, and N fixation), and disturbances are direct C emission (due to forest fires and harvest), C storage change in forest products, and changes in forest age class and cover area. The sum of the individual effects differs from the integrated total due to the interactions between these components. ΔNPP is the NPP departure from the mean equilibrium status before 1895. Both ΔNPP and C balance per unit forest area are in the unit of g C m^{-2} yr^{-1}. Also included are values of the total C balance of Canada's forests in parentheses (Tg C yr^{-1}).

(SOA) in the southern BOREAS study area was reported by *W.J. Chen et al.* [1999]. *Jarvis* [1998] reported an average sink of 56 g C m^{-2} yr^{-1} at an old black spruce stand (SOBS) in the southern BOREAS study area in 1994 and 1996. Above a 50-year-old Pacific Northwest Douglas fir stand on Vancouver Island, E.M. Jork et al. (Environmental controls of carbon dioxide fluxes above a Pacific Northwest Douglas-fir forest, submitted to *Agriculture and Forest Meteorology*, 2000) measured a strong C sink of 375 g C m^{-2} yr^{-1} in 1998 and 484 g C m^{-2} yr^{-1} in 1999. Considering the fact that ~3/4 of Canada's forests are located in boreal region and 88.6% of Canada's forests are conifer [*Cihlar et al.*, 1999], we speculate that, on average, Canada's forests not disturbed in recent decades are a small C sink. We emphasize, however, these site data cannot be used to directly validate our regional estimate because the data were site- and age-specific and have large uncertainties. A better comparison can perhaps be made later between site data and model results when spatially explicit NEP calculations are made using remote sensing data.

4.2. Effects of Disturbance Factors Compared With CBM-CFS Estimates

The carbon budget model of Canadian Forest Service (CBM-CFS) [*Kurz et al.*, 1995; *Kurz and Apps*, 1996] estimated C balance of Canadian boreal forests on the basis of age-class distribution resulting from variable disturbance rates. Canadian forests were divided into 457 ecosystem types and 27 age classes [*Kurz et al.*, 1995]. Each type/age class combination was assigned a biomass C content and a soil C content according to forestry inventory data. The total C content and its change (i.e., the annual C balance) during 1920-1989 were then calculated. The effects of changes in climate variables, N availability, and CO_2 fertilization were not considered in the CBM-CFS model. The original application of the model was for 303 Mha Canadian boreal forests. For the purpose of comparison we expand the area to the 417.6 Mha of Canada's forests.

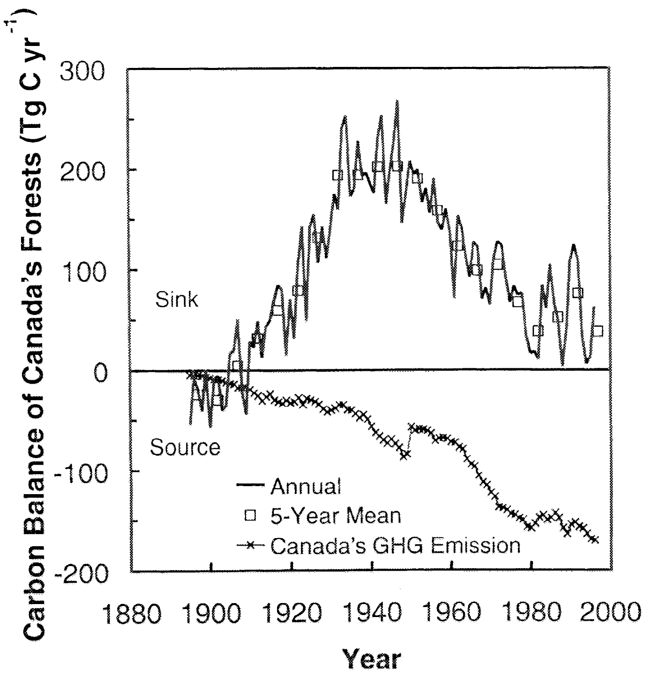

Figure 8. C balance of Canada's forests from 1895 to 1996. Five-year means are plotted, the last point being only the average of 1995 and 1996. Also included is the record of Canada's greenhouse gas C emission rate.

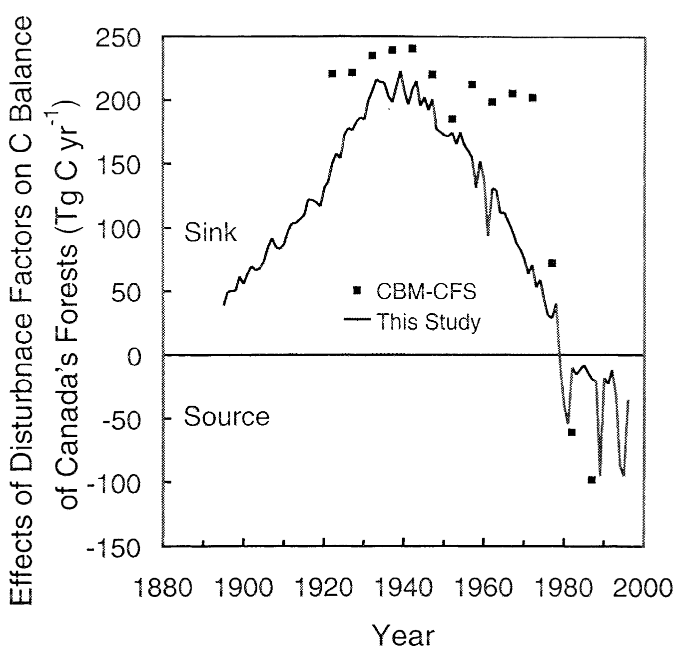

Figure 9. Comparison of the effect of disturbance factors (including forest fire, insect-induced mortality, and harvest) estimated in this study with that of *Kurz* and *Apps* [1996].

Strictly speaking, the relationships between age and growth rate can be derived from forest inventory data only under constant environmental conditions, as changes in environmental conditions may skew these relationships and consequently the final C balance. To circumvent this difficulty, the CMB-CFS model assumed the biomass and growth rate were a function of stand age only within an ecosystem type regardless the time period, and no changes in climate conditions were included in the analysis. For the purpose of comparison, we made the same assumptions in our calculation by using mean NPP and climate conditions over the last 80 years (which is the average age of Canada's forests, [*Kurz and Apps*, 1996]. Figure 9 compares the effects of disturbance factors on C balance of Canada's forests estimated by the CMB-CFS model and by this study. The results agree quite well, in spite of the fact that the two models are independent (Figure 8). The slight difference may be attributed to different methods used in calculating the regrowth rate. Also, we treat Canada's forests as a whole in this study, whereas Kurz et al.'s study used more detailed geographical distributions of disturbances.

Note that the effects of disturbance factors in Figure 9 differ significantly in magnitude from those in Figure 7 because in Figure 7 we kept all nondisturbance factors at the preindustrial levels. This difference suggests that the C balance calculated using the CBM-CFS model might also have been different if a forest inventory had been conducted at the end of nineteenth century and the inventory data had been used to derive the relationship between age and growth rate under the climate conditions of the nineteenth century. This difficulty can only be solved by considering the effects of disturbances under the actual variable climate conditions and NPP values.

4.3. Comparison With C Balance Based on Tree Ring Chronologies

Auclair and Bedford [1997] estimated the volume balance of the world's boreal forests during 1890-1990 in the following way:

$$\text{volume balance} = \text{depletions} - \text{accruals}, \qquad (2)$$

where depletions include pest kill, wildfire, and harvest and accruals include increased growth and regrowth. Pest kill, wildfire, and harvesting were mainly based on data from Canada and Alaska. Regrowth was assumed to start immediately after disturbance and to reach the full volume by a linear increase in growth to maturity at a biome-specific age, and the area-weighted average of tree growth rate in 1990 was 2.18 times of that in 1890 on the basis of tree ring chronology. They converted the forest volume balance to C balance of forest ecosystems by a factor in a range from 4 to 7, i.e., 4-7 tons C storage in biomass and soil of boreal and mixed forest ecosystems per 1 ton of C in volume balance. A sink of 0.8-1.3 Pg C yr^{-1} (1 Pg = 10^{15} g) for the world's boreal forests was estimated during 1970-1990. This factor is much larger than what is found through simulations of the relationship between changes in wood C and ecosystem C pools using InTEC described by *Chen et al.* [this issue] (Figure 10). The conversion equation is $dC_{eco} = 1.0278\ dC_w + 16.036$, where dC_{eco} and dC_w are changes in ecosystem C and wood C, respectively. We suspect that *Auclair and Bedford* (1997) mistook the ratio of total ecosystem C to wood C (C_{eco}/C_w) as that of changes in ecosystem C to wood C (dC_{eco}/dC_w). Due to the cold climate conditions, dC_{eco}/dC_w is generally much smaller C_{eco}/C_w. The offset of 16.036 reflects the fact that harvest and forest fire affected mainly the wood C pool and much less other C pools. In addition, because disturbances, N deposition climate, and CO_2 affect wood C and other C components differently, there is significant scatter in the relationship between dC_{eco} and dC_w. The scatter introduces uncertainties when this equation is used to convert annual forest volume balance [*Auclair and Bedford*, 1997] to the C balance for Canada's forests as a fraction of the total boreal forest. Nevertheless, we found that the trend of these C balance estimates followed closely our model results (Figure 11), although the estimates based on Auclair and Bedford are generally larger than ours, especially during the recent decades. The most likely reason for the remaining difference is that their forest growth rate increased by a factor of 2.18 from 1890 to 1990, whereas we found only 32% increase from 1895 to the recent decades. Forest growth rates derived from tree-ring records usually have large uncertainties, as indicated by the recent study of *Briffa et al.* [1998]. They found that tree growth rates in North America during 1980s were similar to those during 1880s, in contrast to the large increase in growth rates cited by *Auclair and Bedford* [1997].

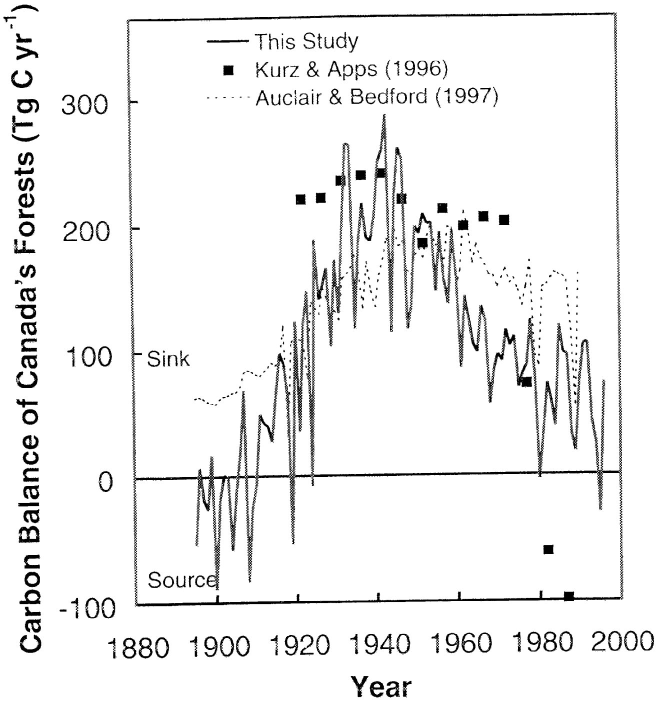

Figure 11. Comparison of C balance of Canada's forests estimated in this study with that derived from *Auclair and Bedford* [1997]. Also included are the estimates of *Kurz and Apps* [1996], who considered disturbance factors only.

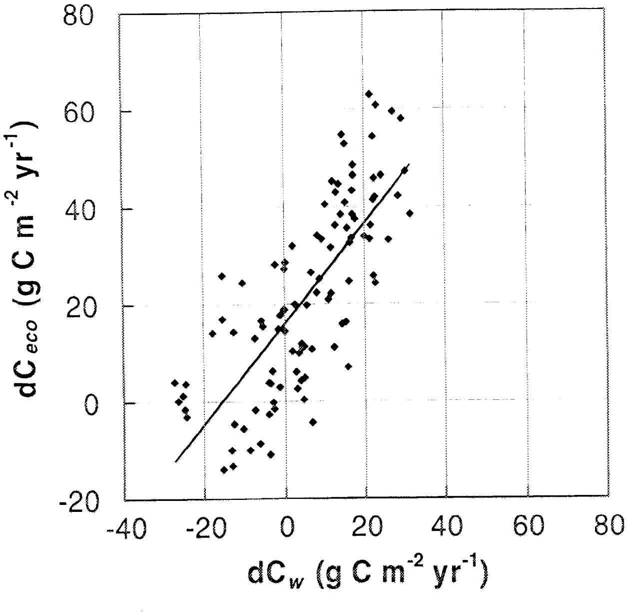

Figure 10. Relationship between changes in wood C pool (dC_w) and in total C storage in forest ecosystems (dC_{eco}): $dC_{eco} = 16.58 + 1.119\ dC_w$, $r^2 = 0.56$.

In 1981, 1986, and 1991, forest inventories were updated in Canada [*Canadian Forest Service*, 1993]. As a result, better forest volume estimates were available for these years, with an accuracy of ±6% nationally [*Auclair and Bedford*, 1997]. These forest volume estimates were only for the commercial forest areas of 234.5 Mha, which is ~56% of Canada's forest area. For the comparison, we assumed that the forest volume of the remaining noncommercial 183.1 Mha of forests had changed at the same rate. Applying the same conversion equation to the volume change in Canada's forests between 1982 and 1991, we calculated a sink of 91 Tg C yr^{-1}. This value is in broad agreement with the sink of 65±33 Tg C yr^{-1} estimated using InTEC for the same period. Caution, however, must also be taken in interpreting this comparison. The overall change in forest volume was only 2.2% from 1981 to 1991, whereas the accuracy of forest volume estimates is reported to be ±6%. The uncertainty in the C balance is thus ~3 times larger than the C balance when forest volumes are used. In view of such an uncertainty, estimates based on physiological principles and historical changes in key factors (e.g., disturbance rates, N deposition, climate, and CO_2 concentration) should be more reliable.

4.4. Comparison With C Balance Inferred From Atmospheric Inversion Analysis

Using an atmospheric inversion technique based on air CO_2 concentration measurements, *Fan et al.* [1998] estimated a sink of 1.7±0.5 Pg C yr^{-1} (1 Pg = 10^{15} g) in North America during 1988-1992, while *Rayner et al.* [1999], using a similar technique, inferred a C sink of only 0.5 Pg C yr^{-1}. For the period of 1988-1992 considered by *Fan et al.* [1998], Canada's forests estimated in this study was a sink of 72±36 Tg C y^{-1}. The estimate based on forest inventories is also a sink of 94 Tg C yr^{-1} for the period of 1987-1991. Using forest inventories and historical landcover change data, *Houghton et al.* [1999] estimated a C sink of 150-350 Tg C yr^{-1} for the United States during 1980s. The combination of these estimates for Canada and the United States suggests that North America (> 15°N) was probably a C sink of 0.2-0.5 Pg C yr^{-1} near the end of the 1980s. The sink strength estimated using these bottom-up modeling and inventory-based approaches for North America is much less than that of 1.7 Pg C yr^{-1} estimated by *Fan et al.* [1998] but is in broad agreement with the estimate of *Rayner et al.* [1999].

5. Summary and Conclusions

This paper reports annual C balance of Canada's forest estimated using the InTEC model. In this study the model was run by treating the entire Canada's forests as one unit. The main findings are the following.

1. If only the effects of changes in nondisturbance factors (N deposition, climate variability, and CO_2 fertilization) were considered, Canada's forests in 1980-1996 would have been a sink of magnitude of ~145 Tg C yr^{-1} or ~35 g C $m^{-2} yr^{-1}$.

2. If only the effects of changes in disturbances (fires, insects, and logging) were considered, Canada's forests in 1980-1996 would have been a source of magnitude of ~56 Tg C yr^{-1}.

3. When the effects of disturbance and nondisturbance factors are integrated, Canada's forests in 1980-1996 are found to be a sink of magnitude of 53±27 Tg C yr^{-1}. Near the middle of this century (1930-1970), Canada's forests were a large sink in the range from 150±75 to 250±125 Tg C y^{-1}, because of regrowth in large forest areas disturbed near the end of the nineteenth century. During 1895-1910, Canada's forests were a small source of 30±15 Tg C yr^{-1} due to large disturbances in late nineteenth century.

Regional C balance cannot yet be measured directly using existing techniques, and therefore it is not yet possible to completely validate our estimates for Canada. However, partial validations have been made based on small-scale measurements, inventory data, and other data. We found the effects of nondisturbance factors are in broad agreement with the results of the CASA simulation run at 1° resolution for Canada [*Potter and Klooster*, 1999]. Site measurements above forest stands at four locations in Canada indicate that Canada's forests that are not disturbed in recent decades are likely a small C sink on average. Our estimates of disturbance effects are consistent with those of *Kurz* and *Apps* [1996], when the same assumptions were made. The overall C balance in the last 100 years varies in a pattern similar to that derived using tree-ring data reported by *Auclair and Bedford* (1997). The sink values of ~65 Tg C yr^{-1} during 1981-1991 were ~30% smaller than the estimates derived from Canadian forest volume change data [Canadian Forest Service, 1993]. Combining these estimates for Canada's forests with that of *Houghton et al.* [1999] for the United States suggests that North America (> 15°N) was probably a C sink of 0.2-0.5 Pg C yr^{-1} during 1980s, much less than the estimate of 1.7 Pg C yr^{-1} by *Fan et al.* [1998] using an atmospheric inversion method.

Although we have taken an approach of comprehensive modeling in order to reduce the uncertainty in C balance estimation, there are still issues that are not considered in this study but may cause additional concerns, as discussed by *Chen et al.* [this issue]. These issues include (1) spatial and temporal variations in climate and N deposition, (2) effects of thaw depth and water table on soil respiration rates, and (3) detailed postdisturbance vegetation dynamics and associated successional biogeochemistry.

Acknowledgments. Funding for this project is provided by CCRS (Canada Centre for Remote Sensing) and by PERD (Panel for Energy Research and Development, Canada) to the senior author. The invaluable assistance of and discussion with many individuals made this research possible: Yiqi Luo, Robert Steward, David Price, Alan Barr, Mike Novak, Andy Black, Ted Hogg, and Sylvain Leblanc. L. Brown internally reviewed the manuscript before submission. The paper also benefited greatly from the constructive comments by three anonymous reviewers and the editor.

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(Received July 26, 1999; revised January 19, 2000;
accepted January 20, 2000.)