ELSEVIER

Forest Ecology and Management 169 (2002) 103–114

Forest Ecology and Management

www.elsevier.com/locate/foreco

Historic carbon budgets of Ontario's forest ecosystems

Jinxun Liu[a,*], Changhui Peng[b,1], Mike Apps[d], Qinglai Dang[a], Edwin Banfield[c], Werner Kurz[d]

[a]*Faculty of Forestry and the Forest Environment, Lakehead University, 955 Oliver Road, Thunder Bay, Ont., Canada P7B 5E1*
[b]*Ministry of Natural Resources, Ontario Forest Research Institute, 1235 Queen Street E., Sault Ste. Marie, Ont., Canada P6A 2E5*
[c]*Natural Resources Canada, Canadian Forest Service, 532-122 Street, Edmonton, Alta., Canada T6H 3S5*
[d]*Natural Resources Canada, Canadian Forest Service, 506 West Burnside Road, Victoria, BC, Canada V8Z 1M5*

Abstract

Carbon (C) budgets of Ontario's forest ecosystems for the period 1920–1990 were calculated using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2). Results show that total forest biomass C in Ontario increased from 1.83 Pg (10^{15} g) to 2.56 Pg between 1920 and 1970, then decreased to 1.70 Pg by 1990. Carbon in soil and forest floor dead organic matter (DOM) increased from 8.30 to 11.00 Pg between 1920 and 1985 but decreased to 10.95 Pg by 1990. Ontario's forest ecosystems acted as a C sink sequestering 41–74 Tg (10^{12} g) C per year from 1920 to 1975, but became a C source releasing 7–32 Tg C per year (5-year average) after 1975. Disturbances (fire, insects and harvesting) enhanced both direct and indirect C emissions, and also affected average forest age and C sequestration. Net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) were affected by both disturbances and average forest age. Forests in the boreal (BO, 62.66 M ha), cool temperate (CT, 7.77 M ha) and moderate temperate (MT, 0.20 M ha) regions had different C dynamics. However, boreal forests dominated Ontario's forest C budget because of the large area and associated C stock. Detailed C budgets for 1990 were also analyzed. The average forest ages in 1990 were 36.2 years for BO, 43.4 years for CT, and 92.1 years for MT regions, respectively. The total C stock of Ontario's forest ecosystems (excluding peatlands) was estimated to be 12.65 Pg, including 1.70 Pg in living biomass and 10.95 Pg in DOM and soil. Average C density was 179 Mg ha^{-1} (10^6 g) (24 Mg ha^{-1} for biomass and 155 Mg ha^{-1} for DOM and soil). The total net C balance (excluding harvest removal) was −31.8 Tg. NPP, NEP and NBP were 267.6, −28.2 and −40.6 Tg per year, respectively. The young age (36.2) of Ontario's boreal forests indicates a great potential for C sequestration and storage. Roughly 1 Pg C could be sequestered with a 10-year increase in forest age. A less severe disturbance regime and/or higher NPP would convert Ontario's forest ecosystems back to a C sink.

Keywords: Climate change; Net primary production; Net ecosystem production; Net biome production; Carbon Budget Model; Kyoto protocol; Disturbances

1. Introduction

Carbon dioxide (CO_2) is a major greenhouse gas (GHG) and its concentration in the atmosphere has been increasing steadily since the beginning of its measurements in 1958 (Keeling et al., 1989). Because forests and forest soils have large capacities both to

---

[*] Corresponding author. Present address: Department of Geography and Program in Planning, University of Toronto, 100 St. George St., Room 5047, Toronto, Ont., Canada M5S 3G3.
Tel.: +1-416-946-7715; fax: +1-416-946-3886.
E-mail address: liuj@geog.utoronto.ca (J. Liu).

[1] Present address: Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, 501 E. St. Joseph, Rapid City, SD 57701-3995, USA.

0378-1127/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0378-1127(02)00301-8

store and release carbon (C) (Cannell et al., 1992; Dixon et al., 1994), detailed forest ecosystem C budgets are helpful for C management.

Under the Kyoto protocol, Canada has agreed to reduce its GHG emissions by 6% by 2010 from the 1990 level. With 38% of Canada's population and 17% of Canada's forestland, Ontario plays an important role in Canada's C budget. Ontario needs to investigate its C budget in detail and report on its C sinks and sources to help meet the national commitment. For this reason, the Ontario Ministry of Natural Resources (OMNR) has developed a strategic approach to the design and implementation of climate change programs (Colombo et al., 1998; OMNR, 1999).

In the past two decades, C budget studies have become increasingly more important, particularly in the areas of climate change, land use, and sustainable forest management. Several global and international C budget studies have been implemented in the past decade (Brown et al., 1993, 1996; Winjum et al., 1992, 1993; Dixon et al., 1994; Houghton, 1996). National scale C budgets have also been studied in many countries, for example, Canada (Kurz et al., 1992; Kurz and Apps, 1999), United States (Delcourt and Harris, 1980; Turner et al., 1993, 1995ab; Birdsey and Heath, 1995), New Zealand (Hollinger et al., 1993), the former Soviet Union (Vinson and Kolchugina, 1993; Krankina and Dixon, 1994), Finland (Kauppi et al., 1992; Kauppi, 1997), Brazil (Schroeder and Winjum, 1995a, 1995b; Schroeder, 1996), Spain (Murillo, 1997), Australia (Gifford, 1992; Gifford and Barson, 1992), China (Wang, 1999), Sweden (Eriksson, 1991), and Britain (Cannell and Milne, 1995). However, only a few studies have reported provincial C budgets (Kurz et al., 1996b; Peng et al., 2000).

Carbon budgets are generally quantified using a C budget model or calculated from a forest inventory database (Brown et al., 1996). The model approach is usually used when incomplete inventory data are available, especially for historic C budget analyses. A C budget model's framework is usually based on the basic structure and function of major ecosystems for C pool and flux.

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) is a well-established model that has already been applied at national (Kurz and Apps, 1995, 1996, 1999), provincial (Kurz et al., 1996b), and forest management unit scales (Price et al., 1996, 1997; Kurz et al., 1998). We investigated the 1920–1990 C budget of Ontario's forest ecosystems using this model. The objectives of this study were to (1) calculate the C stocks and fluxes of Ontario's forest ecosystems in 1990, (2) represent and analyze the effect of past disturbances on the C budget dynamics in Ontario's forest ecosystems and (3) identify the uncertainties, gaps, and future challenges of fully quantifying the dynamics of Ontario's forest C budget.

2. Materials and methods

2.1. General model description

The CBM-CFS2 is a stand and landscape-level model of C dynamics in biomass and dead organic matter (DOM) C pools. It considers six biomass C compartments and four DOM C compartments (Fig. 1). The DOM C pools include coarse woody debris, surface litter and soil C. Carbon dynamics are simulated by accounting for forest growth, biomass allocation, litterfall, tree mortality, DOM decomposition and emissions, and the impacts of disturbances on ecosystem C transfers and releases to the atmosphere.

The CBM-CFS2 model is designed to investigate C budgets using forest inventory data and can be applied at spatial scales from stands to all of Canada. Forest inventory data used in this study were derived from the National Forest Biomass Inventory database (Bonnor, 1985). Model inputs include area, forest type, forest age, site condition, disturbance statistics, including harvesting and natural disturbances, and management activities such as planting. Model outputs include the C stocks and fluxes of the forest ecosystem. The model also uses the Oak Ridge National Laboratory (ORNL) soil data for initialization, and historic disturbance data for simulation of the initial DOM C pools (Kurz and Apps, 1999).

Simulations were run for the period 1920–1990 using a 5-year time step. The initial forest age class structure in 1920 was estimated from the forest inventory data for 1970 and the disturbance history between 1920 and 1970 using an iterative approach. The details of the procedure implemented to estimate the 1920 age class structure are described and discussed by Kurz and Apps (1999).

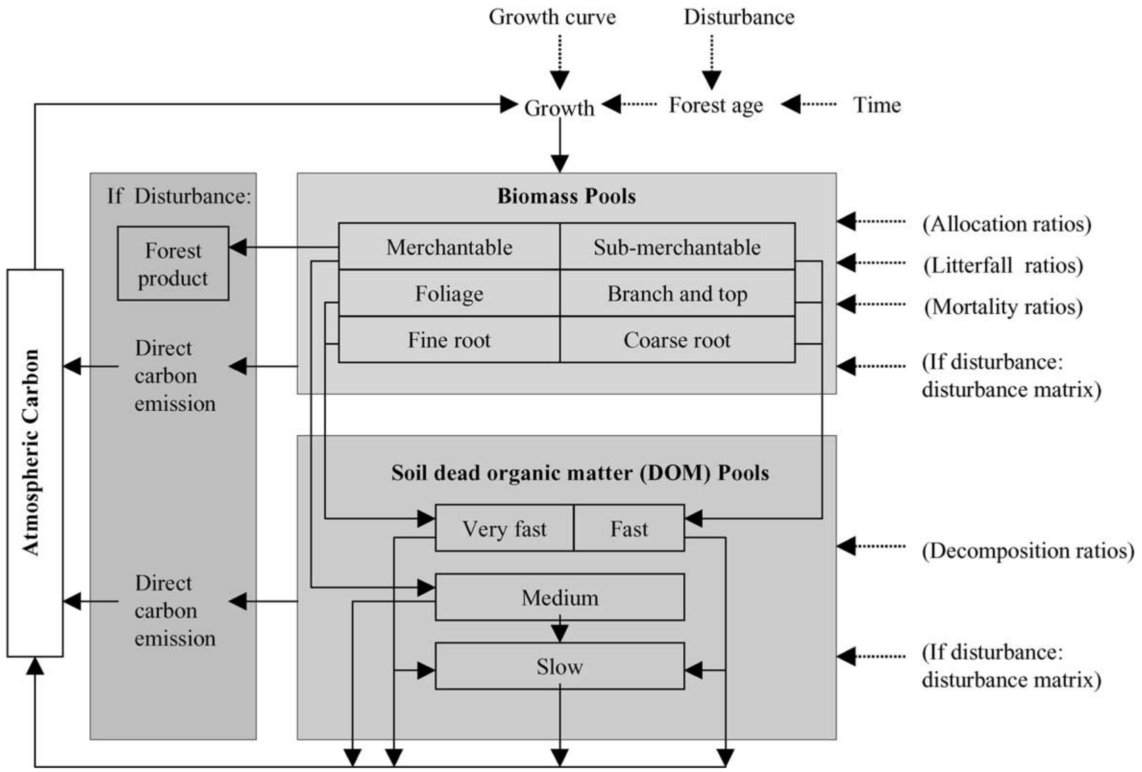


Fig. 1. Flow chart of CBM-CFS2.

2.2. Ecoclimatic regions of Ontario and spatial units in the CBM-CFS2

Based on the national classification of ecoclimatic provinces (Ecoregions Working Group, 1989), Ontario is divided into four ecoregions: sub-arctic (SA), boreal (BO), cool temperate (CT), and moderate temperate (MT) (Fig. 2). These regions are represented as spatial units in the CBM-CFS2. The SA region has no forests in the inventory. The other three regions are further classified into 45 forest ecosystem types using inventory classifiers such as land class, productivity, stocking, forest type, and site quality. Each forest ecosystem type is further divided by forest age classes (at 5-year intervals) for C budget accounting. Although the area and characteristics of forests within each spatial unit is known from the inventory, the spatial locations of forest ecosystem types or age classes within each spatial unit are not tracked.

2.3. Forest growth, litterfall, tree mortality, and soil carbon dynamics

In the CBM-CFS2, forest biomass growth is simulated using four-phase (i.e., regeneration, immature, mature, and over-mature) growth curves. The growth curves were developed from forest biomass inventory data (see Kurz and Apps, 1999), and are specific to each spatial unit and forest ecosystem type. Annual tree biomass increment (or growth rate) is defined by the growth curve.

A pair of tree growth curves (one each for hardwood and softwood species) is associated with each forest ecosystem type. Forest ecosystem types are classified by administrative province, ecoclimatic province, land class, productivity, forest stocking, forest type, and site quality. Currently, 45 forest ecosystem types with 90 growth curves are used for Ontario. Biomass growth of a stand depends on the growth curve (which

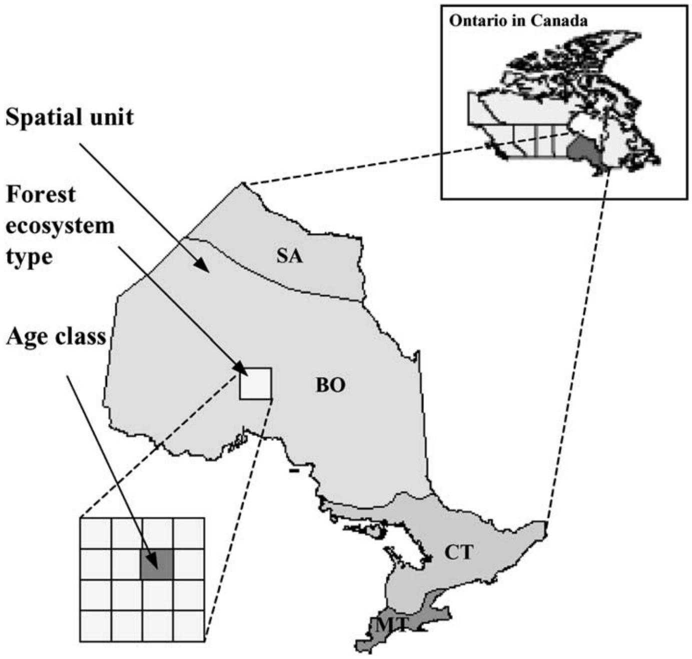


Fig. 2. Ecoclimatic regions of Ontario and three spatial levels in CBM-CFS2. SA, BO, CT, MT refer to sub-arctic, boreal, cool temperate and moderate temperate regions, respectively.

is selected based on the ecosystem type) and the stand's age. The biomass pool is the net accumulation of annual biomass growth (before disturbance) deducting the biomass lost through disturbances.

Living biomass of each softwood and hardwood component in each forest type is divided into six components: foliage, branches and tops, sub-merchantable stems, merchantable stems, fine roots, and coarse roots. Each aboveground component has a specific biomass allocation ratio that expresses its proportion of the whole tree biomass. Belowground biomass (coarse and fine roots) was estimated using regression equations developed by Kurz et al. (1996a).

Annual litterfall from living tree components is determined by litterfall rates. In the boreal region, for example, annual litterfall rates for softwood foliage, hardwood foliage, stemwood, branches, and coarse roots are 0.05, 0.95, 0.006, 0.03, and 0.02 of the corresponding biomass pool, respectively. Forests may become over-mature after forest stands keep maintaining their highest biomass (the mature state) for some years (by default 10 years). Unless inventory data indicate no stand-break up in over-mature stands, biomass pools decrease at a rate defined from the inventory data, or at a rate of 2% per year for hardwood species and 1% per year for softwood species. When the biomass of the over-mature forest drops to 20% of its mature-phase biomass, the forest is reset to the immature growth phase and growth resumes at the rate defined in the growth curve.

The DOM pools in soil are divided into four subpools characterized by their turnover times: very fast, fast, medium, and slow (Fig. 1). These pools receive C through litterfall, tree mortality, and disturbance. The very fast pool receives C from foliage and fine roots. The fast pool receives C from branches/tops, sub-merchantable parts, and coarse roots. The medium pool receives C from merchantable stems. The slow pool represents humus and receives decomposed C from the other three soil pools. Each pool has a different decomposition rate that is modified according to the mean annual temperature of each spatial unit (Kurz et al., 1992). At the time of disturbance, C transfer among C pools, releases to the atmosphere and transfers to the forest product sector are determined by disturbance matrices that are specific to

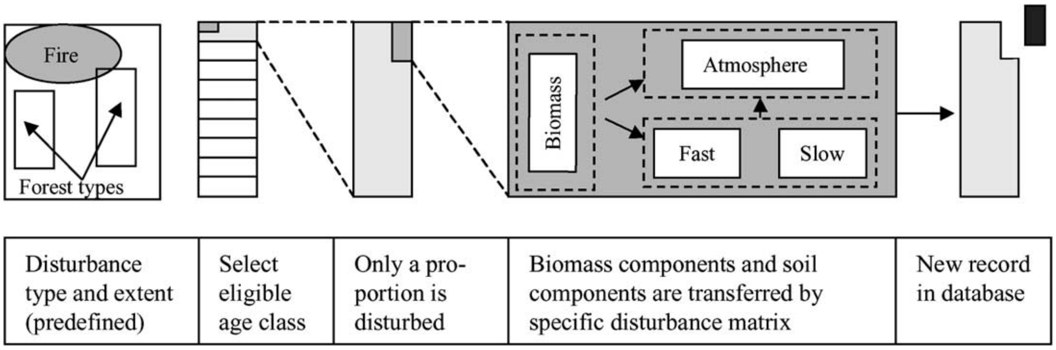


Fig. 3. Fire disturbance scheme used in CBM-CFS2.

ecoclimatic provinces and disturbance types. Biomass allocation ratios, litterfall ratios, soil decomposition ratios, and disturbance matrices were derived from various published and unpublished sources (Kurz et al., 1992; Kurz and Apps, 1999).

2.4. *Disturbances*

The CBM-CFS2 explicitly identifies seven types of disturbances: wild fire, insect-induced stand mortality, clearcutting, clearcutting with slash burning, salvage

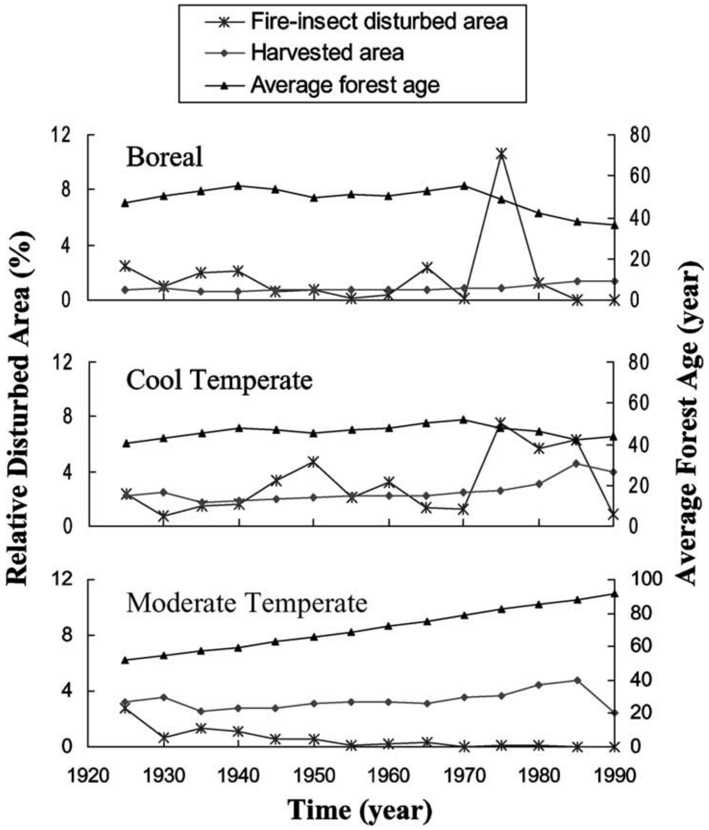


Fig. 4. Disturbance history and dynamics of average forest age in Ontario.

logging following fire, salvage logging following insect-induced stand mortality, and partial cutting. For each spatial unit, seven specific disturbance matrixes are provided to account for related C transfers (Kurz et al., 1992). Stand-replacing disturbances interrupt normal stand development and move the stand into the regeneration stage.

For retrospective simulations, the area disturbed at each time step is an input variable to the model. When a disturbance occurs, the model first selects the forest records (representing a particular forest ecosystem type, age and disturbance history) for areas that are eligible for a particular disturbance, and then applies rules to select records from the list of those eligible for this disturbance. A disturbed record is usually divided into two parts. The unaffected portion updates the original record in the database except that its area has changed. The disturbed portion switches to a new age class, usually the beginning of regeneration, and forms a new record. New records are thus formed in every time step. For record management, records with similar characteristics can be merged based on user-defined criteria, in which case the area-weighted content of each pool is calculated (Fig. 3).

2.5. Forest ecosystem productivity

Net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) are indices that describe the functionality of ecosystems (when we consider ecosystem at a large regional level such as Ontario, we can use NBP for ecosystem, although biome is defined as a higher level than ecosystem). In this study, NPP was calculated as annual ecosystem biomass increment plus annual litterfall (before disturbances). NEP was calculated as NPP minus soil C emissions, representing the net C balance of forest ecosystems (before disturbance). NBP was calculated as NEP minus harvest removals and direct C emissions caused by disturbances.

3. Results

3.1. Historic carbon budgets

Historic C budgets were simulated at 5-year intervals from 1920 to 1990. In the BO and CT regions, average forest age declined during 1940–1950, and 1970–1990. Forest age fluctuations had more obvious relationship to harvest than to forest fire and insect disturbances (Fig. 4). Harvests in the BO and CT regions were usually clearcutting and clearcutting with slash burning. As harvested area increased, average forest age decreased. With lower harvesting activity and lower fire/insect disturbance, the average forest age in the CT region increased during 1985–1990. In the MT region, fire and insect disturbances were much lower than BO and CT regions. Relative harvested areas in MT region were higher than that in BO and CT regions, but harvesting was mainly through partial cuttings during the study period. The forest age of the MT region increased steadily since the 1920s.

NPP of forest ecosystems fluctuated with forest age. During the study period, NPP ranged from 3.55 to 4.77 Mg C ha^{-1} per year $(1\ \mathrm{Mg} = 10^6\ \mathrm{g})$ for BO, 4.82–6.54 Mg C ha^{-1} per year for CT, and 5.40–12.00 Mg C ha^{-1} per year for MT regions (Fig. 5). NPP outputs indicate that forests in southern Ontario

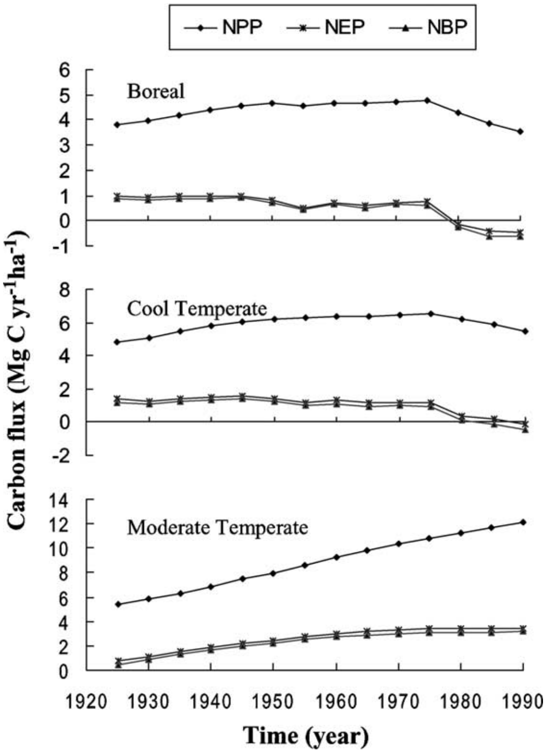


Fig. 5. NPP, NEP, and NBP of Ontario's forest ecosystems.

had higher productivity than forests in northern Ontario. NEP and NBP of the BO and CT regions were usually around 1.0 Mg C ha^{-1} per year before 1975, but decreased significantly after 1975 and even became negative after 1975 due to disturbances.

Carbon emission was strongly influenced by disturbances, especially the transfer rate of biomass C into DOM C following disturbance. Direct C emission under a disturbance (i.e., combustion during a fire and insect respiration in insect disturbances) was less than indirect C emission produced by the decomposition of the additional biomass transferred to DOM pools by a disturbance. Indirect C emissions caused by disturbances were not immediately reflected in the estimates because of a time lag from DOM pools through the slower processes of decomposition. In the BO region, the C budget changed from a sink of 61.1–31.6 Tg C per year during the first decline of forest age (1940–1950). During the second decline of forest age (1970–1990), the C budget decreased from a sink of 44.1 Tg C per year to a source of −31.4 Tg C per year. Similar trends were also found in the CT region (Fig. 6). Fig. 7 shows the dynamics of biomass C and DOM C in Ontario's forests. The biomass and DOM C of boreal forests were related to average forest age. DOM C stock increased with average forest age. When forest age decreased, DOM C stock slowed their increase or began to decline.

In general, forests in the CT region showed dynamics similar to that of the boreal forests. However, forests in the MT region did not experience age declines (i.e., no heavy disturbances) and continued to accumulate C along with increases in NPP, NEP, and C emissions. The CT region maintained a positive NBP (C sink) over the study period and remained more productive (at a more mature forest age) than BO and CT regions.

3.2. 1990 carbon budget

The year 1990 is the base reference year for the Kyoto protocol. The end point of our simulation was

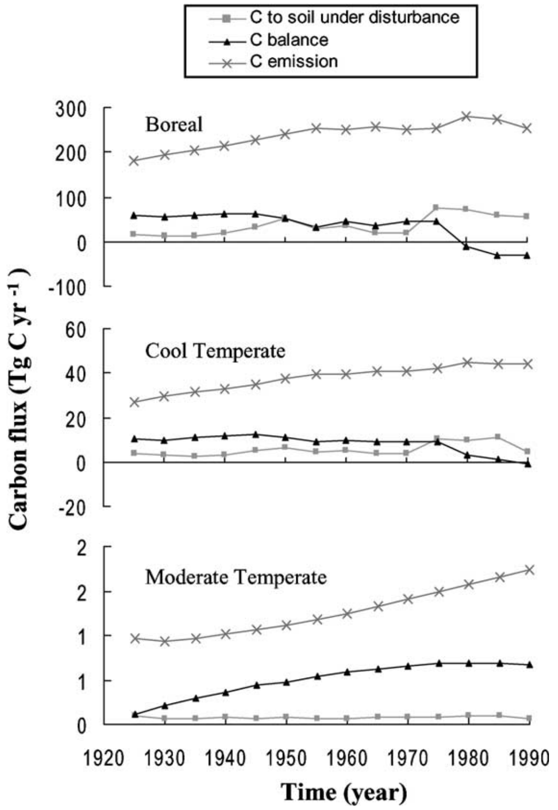


Fig. 6. Carbon budgets of Ontario's forest ecosystems.

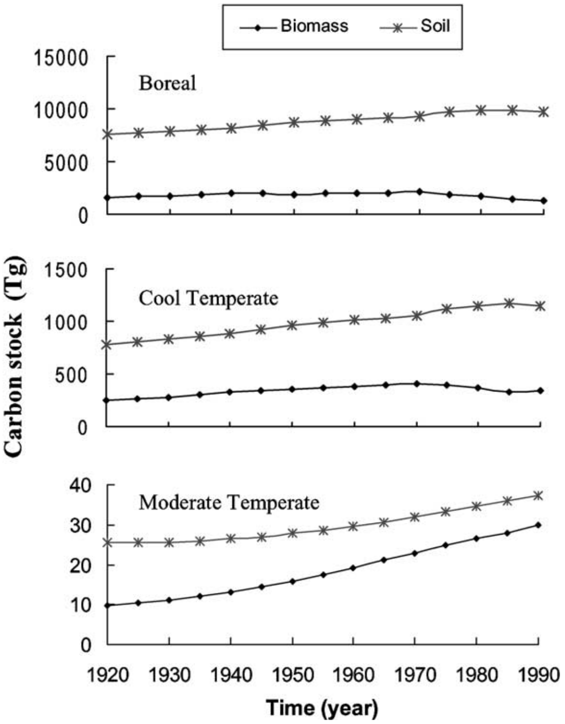


Fig. 7. Historic biomass carbon and soil carbon stocks in Ontario's forests.

Table 1
General properties of Ontario's forest ecosystems in 1990

Region	Forest ecosystem types	Average forest age (year)	Forest land area (M ha)	Biomass C stock (Tg)	Litter and soil C stock (Tg)	Biomass C density (Mg ha^{-1})	Litter and soil C density (Mg ha^{-1})
Boreal	15	36.2	62.66	1336	9761	21	156
Cool temperate	16	43.4	7.77	336	1148	43	148
Moderate temperate	14	92.1	0.2	30	37	149	187
Sum	45	37.2	70.64	1702	10946	24	155

the end of 1989 or beginning of 1990. Since the model's input and output used a 5-year time step and since we did not have properly prepared data for simulation after 1990 at the time of this study, we used the last 5-year's model outputs to estimate the closest C budget of 1990. General forest C related features of Ontario's forests in 1990 are provided in Table 1.

3.2.1. Carbon stocks

Biomass and DOM C stocks in the BO, CT, and MT regions in 1990 are shown in Table 2. Biomass C stocks were estimated to be 12.1, 22.8, and 44.4% of total ecosystem C stock in each region for BO, CT, and MT, respectively, showing an increasing gradient of biomass C from north to south. The six biomass components had similar C percentages within the ecosystem, except in the MT region where sub-merchantable biomass was very low. This indicates that the MT forest ecosystem had fewer young and immature trees at the time.

Among the three regions, the percentage of fast plus very fast DOM C was 16.3% for BO, 17.3% for CT, and 20.5% for MT. The slow DOM pool in each region accounted for 71–78% of total DOM C, representing the largest C pool in each region.

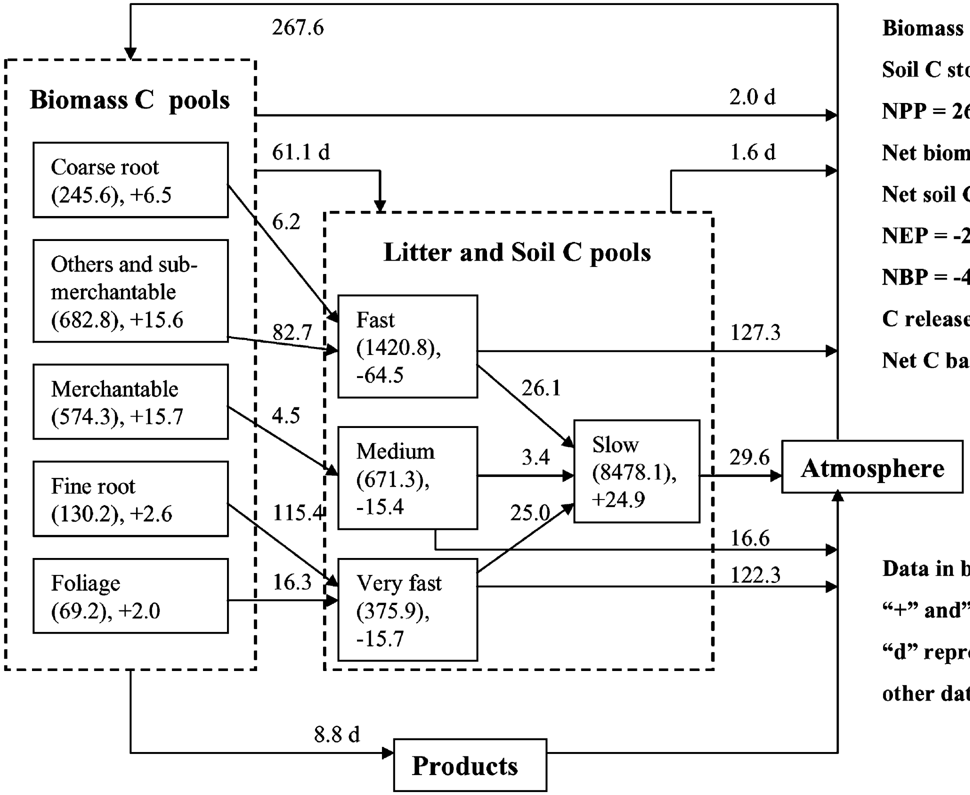
3.2.2. Carbon fluxes

The overall C flux and stocks of Ontario's forest ecosystems are shown in Fig. 8. The total net C sequestering through forest growth (NPP) was estimated at 267.6 Tg C per year ($1\ \mathrm{Tg} = 10^{12}$ g). Carbon uptake by BO, CT, and MT regions was 83, 16, and 1% of the total C uptake in Ontario, respectively. About 299.4 Tg C per year (including direct C emission) was released to the atmosphere. Carbon release from BO, CT, and MT regions was 85, 14 and 1% of the total C emissions in Ontario, respectively.

The NEP of the overall forest ecosystem was −28.2 Tg C per year. NBP was −40.6 Tg C per year (including all disturbances). The net balance of C sequestration and emission was −31.8 Tg per year

Table 2
Carbon stocks in Ontario's forest ecosystems in 1990 (Tg C)

Region	Foliage	Branch and top	Sub-merchantable	Merchantable	Fine root	Coarse root	Total
Biomass							
Boreal	59.8	196.2	352	429.3	110.6	188.6	1336.4
Cool temperate	8.7	60.3	66.1	129.2	18.9	52.5	335.8
Moderate temperate	0.7	7.1	1	15.8	0.7	4.5	29.8
Sum	69.2	263.6	419.1	574.3	130.2	245.6	1702
Region	Very fast	Fast	Medium	Slow			Total
Soil							
Boreal	340.4	1250.2	590.3	7579.8			9760.7
Cool temperate	34.4	164	77.7	871.9			1148.1
Moderate temperate	1.1	6.6	3.3	26.4			37.4
Sum	375.9	1420.8	671.3	8478.1			10946.2



Biomass C stock = 1702.0 Tg = 1.70 Pg

Soil C stock = 10946.2 Tg = 10.95 Pg

NPP = 267.6 Tg yr^{-1}

Net biomass C increment = 42.5 Tg yr^{-1} (before disturbance)

Net soil C increment = -70.7 Tg yr^{-1} (before disturbance)

NEP = -28.2 Tg yr^{-1}

NBP = -40.6 Tg yr^{-1}

C release = 299.4 Tg yr^{-1} (only to atmosphere)

Net C balance = -31.8 Tg yr^{-1} = -0.03 Pg yr^{-1}

Data in brackets show C stock at the end of simulation,
“+” and” -” indicate net C change before disturbance,
“d” represents C flow caused by disturbance,
other data indicate C flow beyond disturbance

(1 Pg C = 10^3 Tg = 10^{15} g C)

Fig. 8. Carbon stocks (Tg) and fluxes (Tg per year) of Ontario’s forest ecosystems in 1990.

Table 3
Age class structure of Ontario's forests in 1990

Age (year)	Boreal (M ha)	Cool temperate (M ha)	Moderate temperate (M ha)
10	26	2.45	0.4
30	8.6	1.11	1.3
50	10	1.38	6.5
70	11.8	1.67	80.5
90	6.1	1.1	77.3
110	0	0.03	13.5
130	0	0.01	5
150	0	0.01	2.8
170	0	0	1.5
190	0	0	2
200	0	0	9.5

(not including harvest removal), indicating Ontario's forest ecosystems were a net C source in that year.

The C balance of individual regions indicated that BO was a C source with −31.5 Tg C per year net emission, CT was a source with −1.1 Tg C per year, and MT was a C sink with 0.7 Tg C per year. However, these figures do not account for C storage or emission from the forest products sector or in peatlands.

For Ontario's forests in 1990, the net biomass C increment before disturbance was 42.5 Tg C per year, and the net DOM C increment before disturbance was −70.7 Tg C per year. Thus, 1-year's C loss required almost 2 years of forest growth to compensate.

3.2.3. Age class structure

In 1990, the BO and CT regions had similar age class structures (Table 3). The average forest age was only about 40 years, indicating that forests in the BO and CT regions were quite young. In contrast, average forest age in MT region was about 90 years. Forests in the MT region were mostly hardwood species managed on shelterwood or selection system and not subject to major stand-replacing disturbances. Forests under 40 years occupied only 1% of the forest area of MT region, while in BO and CT regions they occupied 55 and 46%, respectively.

4. Discussion and conclusions

The average total C density estimated for 1990 (179 Mg C ha^{-1}) was less than a statistical result from a northern Ontario study that showed a mean C density of 263 Mg C ha^{-1} around late 1980s (Johnston and Uhlig, 2000). Johnston and Uhlig used the data from Forest Ecosystem Classification System (FEC) that resulted in a much higher biomass C density than forest inventory data because the FEC's focus is on mature forest stands over 40 years of age (Johnston and Uhlig, 2000). The CBM-CFS2 accounts for all forest age classes and thus yields a lower average C density. Additional reasons for this discrepancy may include: (1) the CBM-CFS2 model results in this study include all of Ontario's forestlands and thus contain both productive forests and less productive forested areas where both biomass and soil DOM C may be lower than FEC's sample data; (2) the CBM-CFS2 model considers harvesting as a major disturbance that influences C stocks and fluxes, while FEC data come from plots that have not been subjected to harvesting disturbances. Therefore, we think that the results from the CBM-CFS2 model may be more realistic estimations of the C stock and flux for Ontario's forests. However, the effects of forest age, site productivity and disturbances on forest carbon density warrant further detailed investigation. For example, we can develop a subset of CBM-CFS2 data records that are more similar to sample data used by Johnston and Uhlig and compare biomass C and soil DOM C separately for the results produced using the two different methods.

Although the potential future forest C sequestration and C stocks in Ontario could not be calculated at the time of this study, a rough estimate can be made based on historical C dynamics. In the BO region, for example, average forest age increased from 45.2 years in 1920 to 55.2 years in 1940 and C stocks (biomass + DOM) increased from 9.08 to 10.15 Pg during the same period. That amounts to an annual increment of 0.05 or 0.1 Pg C for each 1-year increase in average forest age. Similarly, for the period 1950–1970, the average forest age increased from 49.9 to 55.2 years and C stock increased from 10.67 to 11.36 Pg, a 0.035 Pg C annual increment or 0.13 Pg C for 1-year increase in average forest age. Therefore, decreases in the frequency of stand-replacing disturbances and the subsequent increase in the average age of immature stands will increase the C density and sequestration of the forest. This result demonstrates that the age structure of the forest ecosystems is a key factor in determining the carbon sequestration capacity of Ontario's forests, suggesting that provincial wide planning and monitoring of forest age distribution may be necessary in order to enhance and/or maintain the C storage and sequestration in Ontario's forest ecosystems. Our results suggest that active forest management and protection can play a significant role in controlling the carbon sequestration and storage in Ontario's forests. This study shows that Ontario's forest ecosystems became a C source in the 1980s (−31.8 Tg per year in 1990). This conversion from carbon sink to carbon source was associated with the obvious declines of NEP and NBP that occurred after 1975, forest fires between 1975 and 1985 (Perera et al., 1998) and the subsequent decline of forest age and NPP. Currently intensive forest management practices are being evaluated as strategic mitigation options to enhance forest C sequestration and offset C emissions (e.g., tree improvement, fertilization, changes in rotation length, stocking control and thinning, appropriate harvest method, protecting against fire, insects and disease) (Colombo et al., 1998).

This study suggests that several areas of the CBM-CFS2 need to be improved and/or studies in order to use it to more accurately evaluate the impact of climate change on the carbon storage and sequestration in Ontario's forests. The CBM-CFS2 is a general C accounting framework suitable for C budget calculations at several spatial scales. Sensitivity analyses were previously conducted (Kurz and Apps, 1999). At present however the CBM-CFS2 does not adequately represent the effects of future climate change on C budgets because forest growth rates used in this analysis are derived from empirical growth curves that reflect past forest growth. Future improvements to the model should include more locally defined growth curves and parameters. A model of forest product C budgets has been developed and tested (Apps et al., 1999). Models of the C budget for forested peatlands are also under development. With more data and parameters supporting the framework, further validation and application can be expected.

Acknowledgements

This work was supported by the Climate Change Program of the Ontario Ministry of Natural Resources through a postdoctoral fellowship from Lakehead University to J. Liu. Development of the CBM-CFS2 was funded by the Energy from the Forest (ENFOR) program of the Federal Panel on Energy Research and Development (PERD). We thank R. Phan and H. Jiang for discussion, data preparation, and advice on the CBM-CFS2. Valuable suggestions by two anonymous reviewers are greatly appreciated.

References

Apps, M.J., Kurz, W.A., Beukema, S.J., Bhatti, J.S., 1999. Carbon budget of the Canadian forest product sector. Environ. Sci. Policy 2, 25–41.

Birdsey, R.A., Heath, L.S., 1995. Carbon changes in US forests. In: Joyce, L.A. (Ed.), Productivity of America's Forests and Climate Change. General Technical Report RM-271. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO, 70 pp.

Bonnor, G.M., 1985. Inventory of forest biomass in Canada. Canadian Forest Service, Petawawa National Forestry Institute, Chalk River, Ont., Canada.

Brown, S., Hall, C.A.S., Knabe, W., Raich, J., Trexler, M., Woomer, P., 1993. Tropical forests: their past, present, and potential future role in the terrestrial carbon budget. Water Air Soil Pollut. 70, 71–94.

Brown, S., Shvidenko, A.Z., Galinski, W., Houghton, R.A., Kasischke, E.S., Kauppi, P.E., Kurz, W.A., Nalder, I.A., Rojkov, V.A., 1996. Forests and the global carbon cycle: past, present and future role. In Apps, M.J., Price, D.T. (Eds.), Forest Ecosystems, Forest Management and the Global Carbon Cycle, NATO ASI Series 1: Global Environmental Change, Vol. 40. Springer/Verlag, Heidelberg.

Cannell, M., Milne, R., 1995. Carbon pools and sequestration in forest ecosystems in Britain. Forestry 68, 361–378.

Cannell, M., Dewar, R.C., Thornley, J.H.M., 1992. Carbon flux and storage in European forests. In: Teller, A., Mathy, P., Jeffers, J.N.R. (Eds.), Responses of Forest Ecosystems to Environmental Changes. Elsevier, New York, pp. 256–271.

Colombo, S.J., Cherry, M.L., Graham, C., Greifenhagen, S., McAlpine, R.S., Papadopol, C.S., Parker, W.C., Scarr, T., Ter-Mikaelian, M.T., 1998. The impacts of climate change on Ontario's forests. Forest Research Information Paper No. 143. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, 50 pp.

Delcourt, H.R., Harris, W.F., 1980. Carbon budget of the southeastern US biota: analysis of historical change in trend from source to sink. Science 210, 321–322.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pool and flux of global forest ecosystems. Science 263, 185–190.

Ecoregions Working Group, 1989. Ecoclimatic regions of Canada, First approximation. Ecoregions Working Group of Canada Committee on Ecological Land Classification. Ecological Land Classification Series, No. 23. Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, Environ. Can., Ottawa, Ont., p. 119 (map at 1:7,500,000).

Eriksson, H., 1991. Sources and sinks of carbon dioxide in Sweden. Ambio 20, 146–150.

Gifford, R., 1992. Implications of the globally increasing atmospheric CO_2 concentration and temperature for the Australian terrestrial carbon budget: integration using a simple model. Aust. J. Bot. 40, 527–543.

Gifford, R., Barson, M., 1992. Australia's Renewable Resources: Sustainability and Global Change. BRR Proceedings No. 14.

Hollinger, D.Y., Maclaren, J.P., Beets, P.N., Turland, J., 1993. Carbon sequestration by New Zealand's plantation forests. NZ J. For. Sci. 23, 194–208.

Houghton, R., 1996. Terrestrial sources and sinks of carbon inferred from terrestrial data. Tellus B 48, 420–432.

Johnston, M., Uhlig, P., 2000. Carbon storage in soils and vegetation among forested ecosystem types in northern Ontario. In Dore, M.H.I., Guevara, R. (Eds.), Sustainable Forest Management and Global Climate Change: Selected Case Studies from the Americas. Edward Elgar Pub., Cheltenham, UK, p. 281.

Kauppi, P., 1997. Carbon reservoirs in peatland and forests in the boreal regions of Finland. Silva Fenn. 31, 13–25.

Kauppi, P., Kari, M., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971–1990. Science 256, 70–79.

Keeling, C.D., Bacastow, R.B., Carter, A.F., Piper, S.C., Whorf, T.P., Heimann, M., Mook, W.G., Roeloffzen, H., 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds. 1. Analysis of observed data. Geophys. Monogr. 55, 165–236.

Krankina, O.N., Dixon, P.K., 1994. Forest management options to conserve and sequester terrestrial carbon in the Russian Federation. World Resour. Rev. 6, 88–101.

Kurz, W.A., Apps, M.J., 1995. An analysis of future carbon budgets of Canadian boreal forests. Water Air Soil Pollut. 82, 321–332.

Kurz, W.A., Apps, M.J., 1996. Retrospective assessment of carbon flows in Canadian boreal forests. In: Apps, M.J., Price, D.T. (Eds.), Forest Ecosystems, Forest Management and the Global Carbon Cycle, NATO ASI Series 1, Global Environmental Change, Vol. 40. Springer/Verlag, Heidelberg.

Kurz, W.A., Apps, M.J., 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. 9, 526–547.

Kurz, W.A., Apps, M.J., Webb, T., MacNamee, P., 1992. The carbon budget of the Canadian forest sector: phase 1. ENFOR Information Report NOR-X-326. Forestry Canada Northwest Region, Edmonton, Alta., 93 pp.

Kurz, W.A., Beukema, S.J., Apps, M.J., 1996a. Estimation of root biomass and dynamics for the Carbon Budget Model of the Canadian Forest Sector. Can. J. For. Res. 26, 1973–1979.

Kurz, W.A., Apps, M.J., Comeau, P.G., Trofymow, J.A., 1996. The Carbon Budget of British Columbia's Forests, 1920–1989: Preliminary Analysis and Recommendations for Refinements. Canada–British Columbia Partnership Agreement on Forest Resource Development: FRDA II. FRDA Report 261. Joint Publication of Canadian Forest Service, Pacific Forestry Centre and BC Ministry of Forests, Research Branch, Victoria, BC, 62 pp.

Kurz, W.A., Beukema, S.J., Apps, M.J., 1998. Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. Mitigation Adaptation Strategies Global Change 2, 405–421.

Murillo, J., 1997. Temporal variations in the carbon budget of forest ecosystem in Spain. Ecol. Appl. 7, 461–469.

OMNR, 1999. MNR and climate change: a strategic approach to data and information management (a draft). Ontario Ministry of Natural Resources, Unpublished report.

Peng, C.H., Liu, J., Apps, M.J., Dang, Q., Kurz, W.A., 2000. Quantifying Ontario's forest carbon budget. I. Carbon stocks and fluxes of forest ecosystems in 1990. Forest Research Report No. 158. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, 30 pp.

Perera, A.H., Baldwin, D.J.B., Schnekenburger, F., Osborne, J.E., Bae, R.E., 1998. Forest fires in Ontario: a spatial–temporal perspective. Ontario Forest Research Report No. 147. Ontario Ministry of Natural Resources.

Price, D.T., Mair, R.M., Kurz, W.A., Apps, M.J., 1996. Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study. In: Apps, M.J., Price, D.T. (Eds.), Forest Ecosystems, Forest Management and the Global Carbon Cycle, NATO ASI Series 1: Global Environmental Change, Vol. 40. Springer/Verlag, Heidelberg, pp. 279–292.

Price, D.T., Halliwell, D.H., Apps, M.J., Kurz, W.A., Curry, S.R., 1997. Comprehensive assessment of carbon stocks and fluxes in a boreal forest management unit. Can. J. For. Res. 27, 2005–2016.

Schroeder, P., 1996. A carbon budget for Brazil: influence of future land-use change. Clim. Change 33, 369–383.

Schroeder, P., Winjum, J., 1995a. Assessing Brazil's carbon budget. I. Biotic carbon pools. For. Ecol. Manage. 75, 77–86.

Schroeder, P., Winjum, J., 1995b. Assessing Brazil's carbon budget. II. Biotic fluxes and net carbon balance. For. Ecol. Manage. 75, 87–99.

Turner, D.P., Lee, J.J., Koerper, G.J., Baker, J.R. (Eds.), 1993. The forest sector carbon budget of the United States: carbon pools and flux under alternative policy options. EPA/600/3-93/093. US EPA Environmental Research Laboratory, Corvallis, OR.

Turner, D.P., Koerper, G.J., Harmon, M.E., Lee, J.J., 1995a. A carbon budget for forests of the conterminous United States. Ecol. Appl. 5, 421–436.

Turner, D.P., Koerper, G.J., Harmon, M.E., Lee, J.J., 1995b. Carbon sequestration by forests of the United States: current status and projections to the year 2040. Tellus B 47, 232–239.

Vinson, T.S., Kolchugina, T.P., 1993. Pools and fluxes of biogenic carbon in the former Soviet Union. Water Air Soil Pollut. 70, 223–237.

Wang, Y., 1999. Study on regional carbon cycles of forest ecosystems in China. Ph.D. Dissertation. Commission for Integrated Survey of Natural Resources, Chinese Academy of Sciences, Beijing, 80 pp.

Winjum, J.K., Dixon, R.K., Schroeder, P.E., 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. Water Air Soil Pollut. 64, 213–227.

Winjum, J.K., Dixon, R.K., Schroeder, P.E., 1993. Forest management and carbon storage: an analysis of 12 key nations. Water Air Soil Pollut. 70, 239–257.