Influence of disturbance on soil C dynamics in Canadian boreal forests

BHATTI J.S. and **APPS M.J.**

Canadian Forest Service, Northern Forestry Centre, 5320, 122nd Street, Edmonton, Alberta T6H 3S5, Canada

Abstract

In Canadian boreal forest ecosystems, estimates of carbon (C) in the forest floor and total soil were compared and the influence of disturbance was evaluated. The soil C estimates were based on data from: (a) analysis of pedon data from the national-scale soil profile database; (b) the Canadian Soil Organic Carbon Database (CSOCD), which uses expert estimation based on soil characteristics; and (c) model simulations with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2). Estimates for soil C from the three approaches ranged from 1.3 to 5.3 kg C m^{-2} for the forest floor and from 7.8 to 19.2 kg C m^{-2} for the total soil column. Variations in litter input rates due to different type of disturbances cause most of the variation in the soil carbon pools. Changes in disturbance history, litter fall rate, site characteristics, and climatic factors alter the processes regulating both inputs and outputs of carbon to soil stocks. Thus, understanding the dynamics of C as determined by disturbances is essential for quantifying past changes in soil C stocks and for projecting their future change.

Keyword: carbon, soil, litter, disturbances, forests, boreal

Introduction

The boreal or "northern" forest is Canada's largest biome and occupies 35% of the total Canadian land area and 77% of Canada's total forest land, stretching between northern tundra and southern grassland and mixed hardwood trees. Aboveground and belowground biomass, forest floor and mineral soils in Canadian boreal forests contain *ca* 200 Pg C (excluding peat), which represents approximately 15% of the total amount of C stored in the terrestrial biosphere (Apps *et al.*, 1993; Smith *et al.*, 1993). Forest biomass, detritus and soil are the three major pools of carbon in forest ecosystems. Understanding the factors controlling these pools and the exchange of C amongst them and with the atmosphere is critical for estimating the role of forests in the global C cycle. Changes in forest ecosystem C pools are mainly driven by the dynamics of the living biomass. Accumulations of organic C in litter and soil change significantly in respect to forest stands disturbances, such as fire, insects and harvesting. Disturbances transfer biomass C to detritus and soil C pools where it decomposes at various rates over the years following the disturbance. Soil carbon stocks are characterized by long residence times relative to the other biological carbon pools. This is particularly true in boreal and cold temperate zones where the soils have high carbon contents.

Fires and insect outbreak are the two dominant natural disturbance agents of the Canadian boreal forests (Kurz *et al.*, 1995). Changes in fire disturbance regimes over scales of decades and centuries are important explanatory factors of structural, compositional, and functional changes in existing forests (Steijlen and Zackrisson, 1987; Kurz and Apps, 1995). An increase in large-scale, stand-replacing disturbances since *ca.* 1970 has been reported for Canadian forests (Kurz *et al.*, 1995). This has resulted in transitory decreases in net ecosystem productivity and increases in the pools of decomposing organic matter, causing the Canadian boreal forest to become a small net C-source rather than a C-sink (Kurz and Apps, 1995). The change in disturbance regimes for these northern ecosystems may be a response to the larger scale phenomenon of global change, which result from human-induced changes in the physical climate system, land-use changes, and atmospheric pollution (IGBP, 1998).

Understanding the influence of disturbances on the size of soil C pool is essential for evaluating the forest C cycle. In this paper, three estimations of soil carbon in the surface horizon and total soil pools in Canadian boreal forests were compared and the influence of disturbance on C pools of forested ecosystems in the Canadian boreal forests using a simplified version of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2; Kurz and Apps, 1999) are discussed.

Materials and Methods

Study area

Starting in the Yukon Territory, the boreal forest forms a band almost 1,000 kilometres wide sweeping southeast to Newfoundland (Figure 1). To its north is the treeline and beyond that the tundra of the arctic. To its south, the boreal forest is bordered by the subalpine and montane forests of British Columbia, the grasslands of the Prairie Provinces, and the Great Lakes-St. Lawrence forests of Ontario and Quebec. The dominant tree species in the regions are *Populus tremuloides* (aspen), *Picea mariana* (black spruce), *Pinus banksiana* (jack pine), and *Picea glauca* (white spruce). By far the conifer species are well-adapted to the harsh climate, and thin, acidic soils. Black and white spruce are characteristic species of this region along with tamarack, jack pine and balsam fir. Deciduous trees, which are mixed in with the conifers, especially in more southern areas, they may include white birch and poplars.

Pedons soil C database

Data were obtained from the Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils compiled by Siltanen *et al.* (1997). The data were complied from a wide variety of sources (Figure 1). The average sampling depth of a mineral profile in the region was 50 cm. For each horizon, the total quantity of soil C was calculated by multiplying organic C, bulk density, and horizon thickness. Loss on ignition was converted to organic C by dividing by 1.724 (Kalra and Maynard, 1991). Horizons with missing data were assigned values from adjoining, genetically similar horizons in the pedon. The C value thus calculated for each layer was then combined to obtain the total C in each pedon. Missing bulk density information was estimated using an empirical relationship between bulk density and soil organic C content (Grigal *et al.*, 1989).

Canadian soil organic carbon database (CSOCD)

Soil C information together with data attributes were assembled for the boreal zone from existing large scale, soil survey maps and reports. Tarnocai and Lacelle (1996) provided a detailed description of the database, including the database structure, individual attributes, and the methods of calculating the C values. The soil organic C content was initially determined on the basis of individual soil type. Each soil type was allocated a percentage of the grid cell and all grid cells in the database linked to three attribute tables containing information describing the soil landscape and C content. Surface soil C was calculated for the surface 30 cm while total soil C content was calculated to the depth of one meter, but for mineral soils with lithic contact (shallow soils over bedrock) it was calculated for the depth to the contact (if less then one meter). The term "surface layer" refers to the soil organic carbon (content or mass) within the top 30 cm (0 to 30 cm depth) layer of the soil. Although this layer can be composed of both mineral and organic materials, in some cases it is composed entirely of organic materials such as Folisolic and Organic soils or mineral soils with thick (>30 cm) LFH or peaty surface horizons.

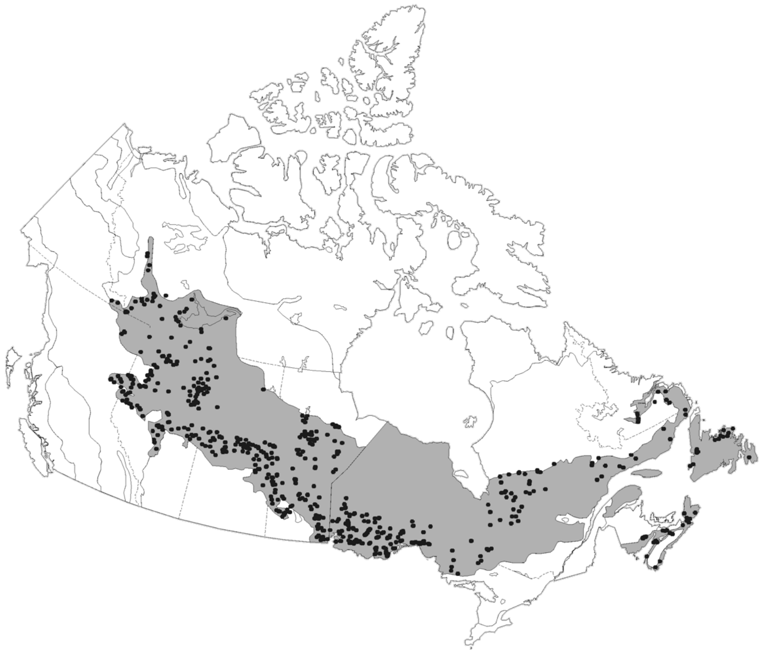

Figure 1 Location of boreal forest ecoclimatic province (grey area) and soil pedons in soil profile and organic C database for Canadian forest and Tundra mineral soils (dots) across Canada.

Carbon budget model of the Canadian forest sector (CBM-CFS2)

CBM-CFS2 is a spatially distributed simulation model, which accounts for C pools and fluxes in forest ecosystems, whose dynamics are primarily driven by stand-replacing disturbances (Kurz and Apps, 1999). In the model, the simulation area is divided into spatial units, having broadly similar vegetation characteristics (Kurz *et al.*,1992; Apps and Kurz, 1993). Within each of these spatial units, the model simulates the dynamics of groups of stands (State Variable Objects, or SVOs) having similar species, composition, productivity, stocking, and age-class characteristics. Soil and litter dynamics are represented by four soil/detritus C pools (designated as very fast, fast, medium, and slow), having different decomposition rates modified by pool type, mean annual temperature, and stand conditions. The slow soil C pool represents humified organic matter and receives C from the three other pools (very fast, fast, and medium) which are loosely associated with forest floor debris (above and below ground). To compare the simulated estimates with the other two approaches, the carbon contents of all four pools are summed to give the total soil C content. Litterfall and mortality are derived from the growth curves and used with a simple soil decomposition model (Kurz and Apps, 1999) to account for changes in litter and soil pools between disturbances.

Results and Discussions

Soil C content in boreal zone

Soil C content in Canadian boreal forest soils ranged from 1.3 to 5.3 kg C m^{-2} for the forest floor and from 7.8 to 19.2 kg C m^{-2} for the total soil column (Table 1). Soil carbon estimates from all three approaches were comparable. The agreement between the CBM-CFS2 simulated values and soil C estimated from field observed data the (methods a) provided an independent test of CBM-CFS2 soil simulations for upland forests. The soil simulations in CBM-CFS2, based primarily on vegetation dynamics and forest inventory data, were only weakly constrained by empirical soil profile data. Soil C estimates from all three approaches are within the range of soil C content reported for forested ecosystems in central Canada (Bhatti *et al.*, 2002), for Canadian soils (Tarnocai, 1998), global boreal forests by Post *et al.*, (1982) (11.1–19.0 kg C m^{-2}), and for North American boreal forests (13.5 – 19.5 kg C m^{-2}) by Pastor and Post (1988). The expert estimation by *CSOCD* yielded higher surface soil C content as compared to two other approches but showed a similar pattern in the surface soil C content for different regions. The higher surface soil C content estimated by CSOCD arises because the contents are reported for upper 30 cm of soil, which may include both forest floor and part of mineral soil. For western boreal zone, CSOCD and CBM-CFS2 modelled total soil C estimates are particularly high as compared to field observed. Since both these approaches are spatial in nature. Elevational differences of only few meters often separate upland forested sites from the poorly drained forested peatland sites in western boreal forest which includes deep organic and peaty soil (organic soil < 40 cm thick) result in higher C content for a given area in CSOCD data base and also higher C content values to initialize and parameterize the model for these regions.

At the regional level, all approaches indicated a higher forest floor soil C content in eastern boreal forest soil (Table 1) than in the western boreal soils. Differences in soil forming factors, including climate, vegetation, parent material, topography, and moisture regime (Jenny, 1980; Goulden *et al.*, 1998), contribute to the differences between the soil C pool of the east and west boreal zone. Climatic conditions, disturbance frequency, forest types, and site properties are some of the important variables contributing to the soil C variation in the forest floor and mineral horizon. Climatic related stresses, such as low moisture content and frequent fire in the western boreal ecosystems result in lower forest productivity (Zoltai *et al.*, 1992) and ultimately lower soil C accumulation in these systems. Grigal and Ohmann (1992) found that stand age is important in explaining the forest floor C content, reflecting the importance of site disturbance history.

Table 1 Field observed, CSOCD and CBM-CFS2 estimation of average C content for boreal forests of Canada.

Region/Provinces	Surface layer ($kg\ C\ m^{-2}$)			Total soil ($kg\ C\ m^{-2}$)		
	Field observed[$] areas	CSOCD[*] forested areas	CBM-CFS2[^] modeled	Field observed areas	CSOCD forested areas	CBM-CFS2 modeled
West						
Northwest Territories	2.7	7.2	2.4	9.8	14.1	11.9
Yukon	5.3	8.5	2.4	11.9	12.8	12.8
British Columbia	2.7	8.2	5.1	9.4	17.7	19.2
Alberta	2.0	5.6	2.8	7.8	10.6	12.8
Saskatchewan	2.8	6.5	3.5	8.2	10.5	14.4
Manitoba	3.1	6.9	3.1	7.8	13.1	14.6
Average	3.1	7.2	3.2	9.2	13.1	14.3
East						
Ontario	3.4	7.0	3.2	9.8	10.7	15.3
Quebec	5.4	14.7	2.4	11.4	16.8	13.2
New Brunswick	2.0	5.4	2.4	16.6	11.6	13.5
Nova Scotia	2.8	2.8	2.5	13.4	9.2	13.9
Newfoundland	4.5	8.4	1.6	14.3	15.1	10.6
Average	3.6	7.7	2.4	13.2	12.7	13.3

[$] Filed observed are from the Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils.
*CSOCD is Canadian Soil Organic Carbon Database in which surface layer is 30 cm deep.
^CBM-CFS2 is Carbon Budget Model of Canadian Forest Sector.

Variations in litter input rates cause most of the variation in the soil carbon pools (Bhatti *et al*, 2000). Simulated litter production for the Canadian boreal forests was 0.35-0.73 kg C m^{-2} yr^{-1}. Litter production rate is regulated by the age-class structure and distribution, which are in turn related to the disturbance type and frequency. Biomass C transfer to detrital pool is expected to be greatest for insect-induced stand mortality (Figure 2), intermediate for fire (as some C will be released directly to the atmosphere as combustion products) and smallest for harvesting (where most of the woody material is transferred out of the forest ecosystem to the forest product sector). Projected climate change scenarios for the boreal forest generally predict warmer and somewhat drier conditions, and are expected to change the disturbance pattern-especially increases in frequency, size and severity-may release C from detritus and soil at higher rates than the rate of C accumulation.

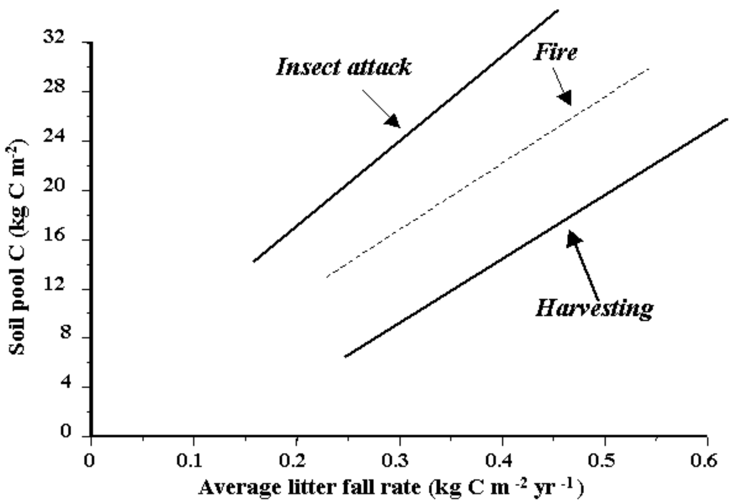

Figure 2 Average C stocks in litter fall and soil C pool for three disturbance types in Saskatchewan boreal forest sites.

Influence of disturbance frequency on soil C dynamics

Carbon accumulating in soil is stable for long times with the difference between litter input and decomposition release changing only slowly. The soil carbon thus may not fluctuate significantly until a disturbance event occurs at the site. The effect of such disturbance is both to provide a pulse of litter carbon (particularly coarse woody debris) and to change the site microclimate and decomposition variables (Apps and Kurz, 1993). There is a significant relationship between CWD and forest floor ($r^2 = 0.86$) as well as total soil C pool ($r^2 = 0.92$). Soil C was strongly affected by the previous disturbance pattern, which influences the present forest age class structure. During a period of apparent low disturbance frequency, the soil C stocks were higher (Figure 3). With higher forest biomass C contributing to a higher litter fall rate, the balance between decomposition losses and litter inputs is achieved at a higher soil carbon value. Therefore, soil appears to act as a C sink during a transition to a lower disturbance frequency, a result previously noted by Kurz and Apps (1995). In contrast, during periods of high disturbance, there was about 10% decrease in soil C content (Figure 3): the soil appears to act as a source of atmospheric C. This observed phenomenon arises for three reasons; i) at the higher disturbance frequency, there is a higher proportion of younger age stands which generate lower litter transfers (as described previously), and for the same reason; ii) there is decreased input of coarse woody debris due to the decrease in proportions of older age stands (Harmon *et al.*, 1990), and iii) an increased rate of decomposition of detritus and soil C pool due to changed microclimate and higher exposure associated with the younger stands (Bhatti *et al.*, 2000). These situations might occur when forest biomass productivity is limited by climate conditions (for example), when input from disturbance is low because of severe fire loss or through harvesting, or when the decomposition rate is high. Therefore, the soil of any individual stand may act as a sink or a source of C depending upon the actual disturbance history of that site.

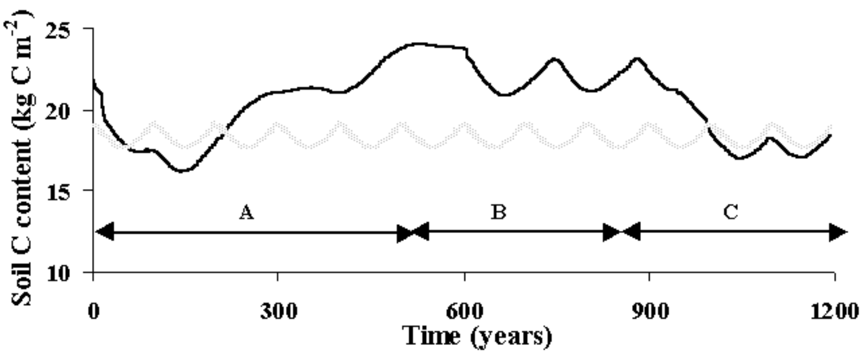

Figure 3 Simulated soil C pools in boreal forest stands using the simplified CBM-CFS2 model over a 1200 year period. Intervals A, B, and C represent intervals of a random sequence that have periods of apparent low, medium and high disturbance respectively

Influence of changing climate on Soil C

Disturbance regimes, both due to fire and insects are affected by climatic conditions through seasonal episodes of drought and elevated temperatures that affect susceptibility of trees to insect attack, fuel loads, and ridging high pressure systems change the probability of lightning (Weber and Flannigan, 1997). Numerous studies have reported higher disturbance frequencies in the last 20 years (Kurz *et al.*, 1995; Woodwell *et al*, 1998). This period has also been a period of elevated temperatures in central and western Canada (Gullett and Skinner, 1992). These two factors have influenced the contemporary rate of net forest C storage in at least three ways: 1) detritus and soil C pool decomposition rates will have increased both due to regional warming and the reduced canopy shading associated with the increase in younger age-stands; 2) decomposable litter and soil C pools associated with disturbance regimes will have increased; and 3) C uptake will have decreased, at least initially, due to the increase in younger age stands with low initial growth rates and regeneration delay.

Using CBM-CFS2, Kurz and Apps (1996) showed that the factors just listed have likely resulted in a net C release from the boreal forests of Canada as a whole. In a companion paper Kurz and Apps (1995) showed that this source period is likely to continue for at least a decade, even if the disturbance regime returns to the averages of previous decades through increased fire protection efforts, for example. This hysteresis arises because of the decade-scale lag times in the dynamics of the biomass, litter and soil pools. It appears that under changing conditions, some parts of the boreal forest may act as a sink of atmospheric C while others act as a source. Further, this spatial complexity can prevail for considerable lengths of time.

Conclusions

In boreal forest ecosystems, the potential for change in the net C balance is strongly influenced by the disturbance pattern. In Canadian boreal forests, the disturbance frequency has increased over the past three decades-a trend that appears to be consistent with that expected from climatic warming-and this has caused significant changes in the net carbon balance at the national scale (Kurz and Apps, 1999). Understanding how these changes might be exacerbated or mitigated in a changing global environment requires linking changes in stand structure with ecosystem processes in vegetation, litter and soils.

The future C balance in boreal forest will largely depend on the type and frequency of disturbance under changing climate conditions. Projected climate change scenarios for the boreal forest generally predict warmer and somewhat drier conditions, and are expected to change the disturbance pattern. Fire and insect predation regimes, for example, are historically sensitive to climate and are expected to change considerably under global warming (Weber and Flannigan, 1998). Altered boreal forest disturbance regimes-especially increases in frequency, size and severity-may release C soil at higher rates. Will the net effect of such changes result in positive feedback to climate change and thereby accelerate global warming (Kurz *et al.*, 1995)?

Acknowledgment

Funding for this study was provided in part by the Federal Panel on Energy Research and Development (PERD).

References

Apps, M.J. and W.A. Kurz. 1993. The role of Canadian forests in the global carbon balance, pp. 14-28. *In* Carbon Balance on World's Forested Ecosystems: Towards a Global Assessment. Proc. of the Intergovernmental Panel on Climate Change Workshop, May 12, 1992. 1993, Joensuu, Finland. Published by Publications of the Academy of Finland.

Apps, M.J., W.A. Kurz, R.J. Luxmoor, L.O. Nilsson, R.A. Sedjo, R. Schmidit, l.G. Simson and T.S. Vinson. 1993. Boreal forest and tundra. Water Air Soil Poll. 70:39-53.

Bhatti, J.S., M.J. Apps and C. Tarnocai. 2002. Estimates of soil organic carbon stocks in central Canada using different approaches. Can. J. Forest Res. 32:805-812.

Bhatti, J.S., M.J. Apps and H. Jiang. 2000. Examining the carbon stocks of boreal forest ecosystems at stand and regional scales, pp. 513-532. *In* R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds.). Assessment Methods for Soil C Pools. CRC Press LLC, Boca Raton.

Goulden, M.L., S.C. Wofsy, J.W. Harden, S.E. Trumbore, P.M. Crill, S.T. Gower, T. Fries, B.C. Daube, S.M. Fan, D.J. Sutton, A. Bazzaz and J.W. Munger. 1998. Sensitivity of boreal forest carbon balance to soil thaw. Science 279:214-217.

Grigal, D.F. and L.F. Ohmann. 1992. Carbon storage in upland forests of the lake states. Soil Sci. Soc. Am. J. 56:935-943.

Grigal, D.F., S.L. Brovold, W.S. Nord and L.F. Ohmann. 1989. Bulk density of surface soils and peat in north central United States. Can. J. Soil Sci. 69:895-900.

Gullett, D.W. and W.R. Skinner. 1992. The state of Canada's climate: temperature change in Canada 1895-1991. SOE Rep. No. 92-2. Environment Canada, Atmospheric Environmental Service, Ottawa, Ontario.

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

Jenny, H. 1980. The Soil Resources. Spring-Verlag, New York.

Kalra, Y.P. and D.G. Maynard. 1991. Methods manual for forest soil and plant analysis. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-319. pp. 116.

Kurz, W.A. and M.J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological Applications 9:526-547.

Kurz, W.A. and M.J. Apps. 1995. An analysis of future carbon budgets of Canadian boreal forests. Water, Air, Soil Pollut. 82:321-331.

Kurz, W.A., M.J. Apps, B.J. Stocks and W.J. Volney. 1995b. Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests, pp. 119-133. *In* G.M. Woodwell and F.T. Mackenzie (eds.). Biotic Feedbacks in the Global Climatic System. Oxford Univ. Press, New York.

Kurz, W.A., K.J. Apps, T.M. Webb and P.J. McNamee. 1992. The Carbon Budget of the Canadian Forest Sector: Phase I. For. Can. North. Reg. North. For. Centre, Edmonton, Alberta. Info. Rep. NOR-X-326, pp. 932.

Pastor, J. and W.M. Post. 1988. Response of northern forests to CO_2-induced climate change. Nature. 334:55-58.

Post, W.M., W.R. Emanuel, P.J. Zinka and G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature. 208:156-159.

Smith, T.M., W.P. Cramer, R.K. Dixon, R.P. Neilson and A.M. Solomon. 1993. The global terrestrial carbon cycle. Water Air, Soil Poll. 70:19-37.

Siltanen, R.M., M.J. Apps, S.C. Zoltai, R.M. Mair and W.L. Strong. 1997. A soil profile and organic carbon data base for Canadian forest and tundra mineral soils. Nat. Resour. Can., Can. For. Ser., North. For. Cent., Edmonton, Alberta. Inf. Rep. Fo42-271/1997E pp. 50.

Steijlen, I. and O. Zackrisson. 1987. Long-term regeneration dynamics and successional trends in northern Swedish coniferous forest stand. Can. J. Bot. 65:839-848.

Tarnocai, C. 1998. The amount of organic carbon in various soil orders and ecoprovinces in Canada, pp. 81-92. *In* R. Lal, J. Kimbla, R.F. Follett and B.A. Stewart (eds.). Soil Processes and the Carbon Cycle. CRC Press Boca Raton.

Tarnocai, C. and B. Lacelle. 1996. Soil Organic Carbon of Canada Database. Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Research Branch, Ottawa, Ontario, Canada (digital database).

Weber, M.G. and M.D. Flanningan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5:145-166.

Woodwell, G. M., Mackenzie, F. T. Houghton, R. A. Apps,M. J., Gorham, E., and Davidson, E. 1998. Biotic feedbacks in the warming of the Earth. Climate Change. 40: 495-518.

Zoltai S, Singh T and Apps M J 1992 Aspen in a changing climate. *In*Aspen Management for the 21st Century. Eds. S Navratil and P B Chapman. pp.143-152. Proc. of Symposium, Edmonton, Nov. 19-21, 1990.