CARBON OFFSET POTENTIALS OF FOUR ALTERNATIVE FOREST MANAGEMENT STRATEGIES IN CANADA: A SIMULATION STUDY

WENJUN CHEN[1,*], JING M. CHEN[1], DAVID T. PRICE[2], JOSEF CIHLAR[1] and JANE LIU[1]

[1]*Applications Division, Canada Centre for Remote Sensing, Canada*

[2]*Northern Forestry Centre, Canadian Forest Service, Canada*

(*Author for correspondence: 588 Booth St., Ottawa, ON, Canada, K1A 0Y7; Tel.: (613) 947-1286; Fax: (613) 947-1406; E-mail: wenjun.chen@geocan.nrcan.gc.ca)*

(Received 11 May 1999; accepted in final form 20 October 1999)

Abstract. Using an Integrated Terrestrial Ecosystem C-budget model (InTEC), we simulated the carbon (C) offset potentials of four alternative forest management strategies in Canada: afforestation, reforestation, nitrogen (N) fertilization, and substitution of fossil fuel with wood, under different climatic and disturbance scenarios. C offset potential is defined as additional C uptake by forest ecosystems or reduced fossil C emissions when a strategy is implemented to the theoretical maximum possible extent. The simulations provided the following estimated gains from management: (1) Afforesting all the estimated ∼7.2 Mha of marginal agricultural land and urban areas in 1999 would create an average C offset potential of ∼8 Tg C y^{-1} during 1999–2100, at a cost of 3.4 Tg fossil C emission in 1999. (2) Prompt reforestation of all forest lands disturbed in the previous year during 1999–2100 would produce an average C offset potential of ∼57 Tg C y^{-1} for this period, at a cost of 1.33 Tg C y^{-1}. (3) Application of N fertilization (at the low rate of 5 kg N ha^{-1} y^{-1}) to the ∼125 Mha of semi-mature forest during 1999–2100 would create an average C offset of ∼58 Tg C y^{-1} for this period, at a cost of ∼0.24 Tg C y^{-1}. (4) Increasing forest harvesting by 20% above current average rates during 1999–2100, and using the extra wood products to substitute for fossil energy would reduce average emissions by ∼11 Tg C y^{-1}, at a cost of 0.54 Tg C y^{-1}. If implemented to the maximum extent, the combined C offset potential of all four strategies would be 2–7 times the GHG emission reductions projected for the National Action Plan for Climate Change (NAPCC) initiatives during 2000–2020, and an order of magnitude larger than the projected increase in C uptake by Canada's agricultural soils due to improved agricultural practices during 2000–2010.

Keywords: afforestation, Canada, C cost, C offset potential, climate change mitigation, forest management, fossil fuel substitution, low-rate N fertilization, reforestation

1. Introduction

Global climate change may be the most critical and complex environmental issue facing humanity over the next century. Global temperatures have increased 0.3–0.6 °C over the last 100 years and are expected to rise by a further 1–3.5 °C by 2100, accompanied by changes in precipitation, storm patterns, and drought frequency and intensity (Santer et al. 1996; Kattenberg et al. 1996). These changes in global climate could significantly affect agricultural production, water supplies, human health, and terrestrial and aquatic ecosystems (Dixon 1997). The 1995 assessment of the Intergovernmental Panel on Climate Change (IPCC) concluded that observed global climate changes can be at least partially attributed to recent increases in atmospheric concentrations of greenhouse gases (GHGs) including CO_2, CH_4, and N_2O (Houghton et al. 1996).

Canada's forests occupy approximately 417.6 million hectares of the land surface, about one tenth of global forest cover (Canadian National Forestry Database, http://www.nrcan.gc.ca/cfs). These forest ecosystems contain about 13 Pg C in aboveground biomass (Kurz et al. 1992), and 38.6 Pg C in soil excluding peaty organic soils (Siltanen et al. 1997). Peaty organic soils contain an estimated additional 168 Pg C (Tarnocai 1997). Even using the lower value for soil C content, a mean annual increase in the C pools of these forest ecosystems of only 0.1% would remove $\sim$52 Tg C y^{-1} (1 Tg = 10^{12} g) from the atmosphere. Several alternative forest management strategies could conceivably be followed to increase C storage in Canada's forest ecosystems. These include: (1) afforestation; (2) prompt reforestation following natural disturbance and harvesting; (3) N fertilization to increase forest productivity; and (4) increased harvesting for direct and indirect substitution of fossil fuel (Price and Apps 1996; Matthews et al. 1996; Brown et al. 1996).

Implementation of these different management strategies would likely cause a large number of interacting effects on forest C pools (including biomass, soils, and wood products), and fluxes (including photosynthesis, plant respiration, soil and litter decomposition, C emission during forest fires and oxidation of forest products). The C biomass pools include wood, foliage, fine roots, and coarse roots, while soil C pools include coarse and fine structural detritus, metabolic detritus, and microbial biomass as well as, slow and passive humus pools. The forest product C pools include construction and other lumber, pulp and paper products, and landfills. Hence, evaluating the C offset potentials and associated C costs of these different management strategies requires a comprehensive analysis. In addition, the effects of anticipated environmental changes, including temperature, precipitation regime and atmospheric CO_2 concentration, must also be considered. An Integrated Terrestrial Ecosystem C-budget model (InTEC) has been developed for this purpose (Chen et al. 1999a). In this study, we used the InTEC model to quantify the C offset potentials of the four alternative management strategies for the next century under different climatic and disturbance scenarios. Following the suggestions of Matthews et al. (1996), we first calculate the baseline C balance without implementing any of these alternatives, and then estimate C offset potential as the difference between the baseline value and that when an alternative strategy is implemented at full scale, under specified climatic and disturbance scenarios. We also compare the projected C offset potentials of these strategies with other proposed GHG reduction programs in Canada.

2. The InTEC Model

The InTEC model is a regional scale C budget model, which calculates the annual C balance of a region in year *i*, *dC*(*i*), as the sum of changes in size of all relevant forest C pools including biomass, $dC_{biomass}(i)$, soil, $dC_{soil}(i)$, and forest products, $dC_{products}(i)$, i.e.,

$$dC(i) = dC_{biomass}(i) + dC_{soil}(i) + dC_{products}(i). \tag{1}$$

The changes in C pool sizes are caused by C fluxes among these pools and between the pools and the atmosphere. Because the inter-pool fluxes cancel when summed, *dC*(*i*) is calculated as the net of all fluxes between the forest C pools and the atmosphere, including net primary productivity (*NPP*(*i*)), soil respiration, and oxidation of forest products (*R*(*i*)), and C emission from forest fires ($\xi A_f(i)$, where ξ is an assumed constant value of C loss per unit burned forest area and A_f (*i*) is the total area burned in year *i*) i.e.,

$$dC(i) = NPP(i) - R(i) - \xi A_f(i). \tag{2}$$

Because the value of *dC*(*i*) is usually an order of magnitude smaller than that of *NPP*(*i*), *R*(*i*), and $\xi A_f(i)$, a 10% error in estimates of *NPP*(*i*), *R*(*i*), and $\xi A_f(i)$ could easily result in a more than 100% uncertainty in *dC*(*i*). To avoid this type of uncertainty, InTEC adopts a relative change approach which consists of the following three steps:

(1) We assume that exchanges of C and N between terrestrial ecosystems and the atmosphere were in equilibrium under the mean pre-industrial conditions of climate (e.g. temperature and precipitation), atmosphere (e.g., CO_2 concentration and N deposition), and disturbance (e.g., fire, insect-induced mortality, harvest), such that

$$dC(0) = NPP(0) - R(0) - \xi A_f(0) = 0. \tag{3}$$

(2) We convert the problem of calculating the net difference between *NPP*(*i*), *R*(*i*), and $\xi A_f(i)$ in equation (2) to a problem of estimating interannual variations in *NPP*, *R*, and ξA_f. Subtracting equation (3) from equation (2) and rearranging the result, gives

$$\begin{aligned} dC(i) &= [NPP(i) - NPP(0)] - [R(i) - R(0)] - [\xi A_f(i) - \xi A_f(0)] \\ &= [\Delta NPP(i) + \ldots + \Delta NPP(1)] - [\Delta R(i) + \ldots + \Delta R(1)] \\ &\quad -[\xi \Delta A_f(i) + \ldots + \xi \Delta A_f(1)], \end{aligned} \tag{4}$$

where Δ*NPP*(*i*) (= *NPP*(*i*)–*NPP*(*i*-1)), Δ*R*(*i*) (= *R*(*i*)–*R*(*i*-1)), and $\xi \Delta A_f(i)$ (= $\xi \Delta A_f(i)$–$\xi \Delta A_f(i\text{-}1)$) are, respectively, the interannual variations of *NPP*, *R*, and ξA_f in year *i*.

(3) We determine Δ*NPP*(*i*), Δ*R*(*i*), and $\xi \Delta A_f(i)$. A new spatial and temporal scaling algorithm is used to determine Δ*NPP*(*i*) (Chen et al. 1999a). The algorithm

is based on the Farquhar leaf photosynthesis model (Farquhar et al. 1980; Bonan, 1995; Luo et al. 1996), which is first scaled up to stand level with a canopy radiation and sunlit/shade leaf separation. We then integrate the instantaneous, relative variations in stand-level photosynthesis, d*NPP*/*NPP*, temporally and spatially to obtain $\Delta NPP(i)$ over a region. Detailed data for photosynthesis and all other variables are required in the integration, but such detailed data are not available for the historical period. To overcome this difficulty, we use the concept of a correlation coefficient, r, between any two variables $x(j)$ and $y(j)$ $\left(\text{i.e., } \sum_{j=i}^{n} x(j)y(j) = n\bar{x}\bar{y}(1 + r\frac{\sigma_x\sigma_y}{n\bar{x}\bar{y}}\right)$, where n is the number of data points, and σ is the standard deviation). In this way, we convert the integration problem to a problem of calculating statistics of mean, correlation coefficient, and standard deviation. These statistics are derived from tower flux measurements of the BOReal Ecosystem-Atmosphere Study (BOREAS, Chen et al. 1999b; Goulden et al. 1998). Using this scaling algorithm, $\Delta NPP(i)$ can be estimated from annual mean atmospheric CO_2 concentration, N deposition, precipitation, disturbance rates, growing season mean temperature and length (determined from mean spring temperature), and NPP determined for a single calibration year. The effect of disturbances on NPP is described through their impacts on forest age class distribution. We estimated the average NPP of Canada's forests in 1994, using the Boreal Ecosystems Productivity Simulator (BEPS) (Liu et al. 1997; Chen et al. 1999c). Inputs required by BEPS include land cover and leaf area index maps derived from 1-km resolution AVHRR data at 10-day intervals, soil texture, and daily meteorological data. We calculate $\Delta R(i)$ using a modified version of the Century model (Parton et al. 1987; Schimel et al. 1996), with NPP inputs obtained from the above procedures. The climatic effects on decomposition rate are estimated using a modified Arrhenius-type equation (Lloyd and Taylor 1994). The value of $R(0)$ is determined using Equation (3). At an annual time step, the net N mineralization associated with decomposition is also estimated and provides a negative feedback to NPP; hence decomposition and photosynthesis processes are closely coupled in the InTEC model.

In this study, the original InTEC model was expanded to simulate C cycling in forest products by including the following components: landfills, recycling of lumber and pulp products, and use of wood products as energy substitutes for fossil fuels (Figure 1). We also divide lumber into construction lumber and other lumber, and burned wood into bioenergy and waste components, following Kurz et al. (1992). The partitioning coefficients for initial forest products (i.e., sawlogs, pulpwood, and fuelwood) and secondary products (i.e., recycled lumber and pulp materials) are given in Table I, based on statistics obtained from the Canadian National Forestry Database Program (www.nrcan.gc.ca/cfs) and Kurz et al. (1992). Recycling is defined as the fraction of each pool which is transferred to itself at the end of each accounting period. Table II lists turnover rates and fossil fuel substitution coefficients, following Kurz et al. (1992), Houghton (1993), and Schlamadinger and Marland (1996). Landfilled material is further divided into 80%

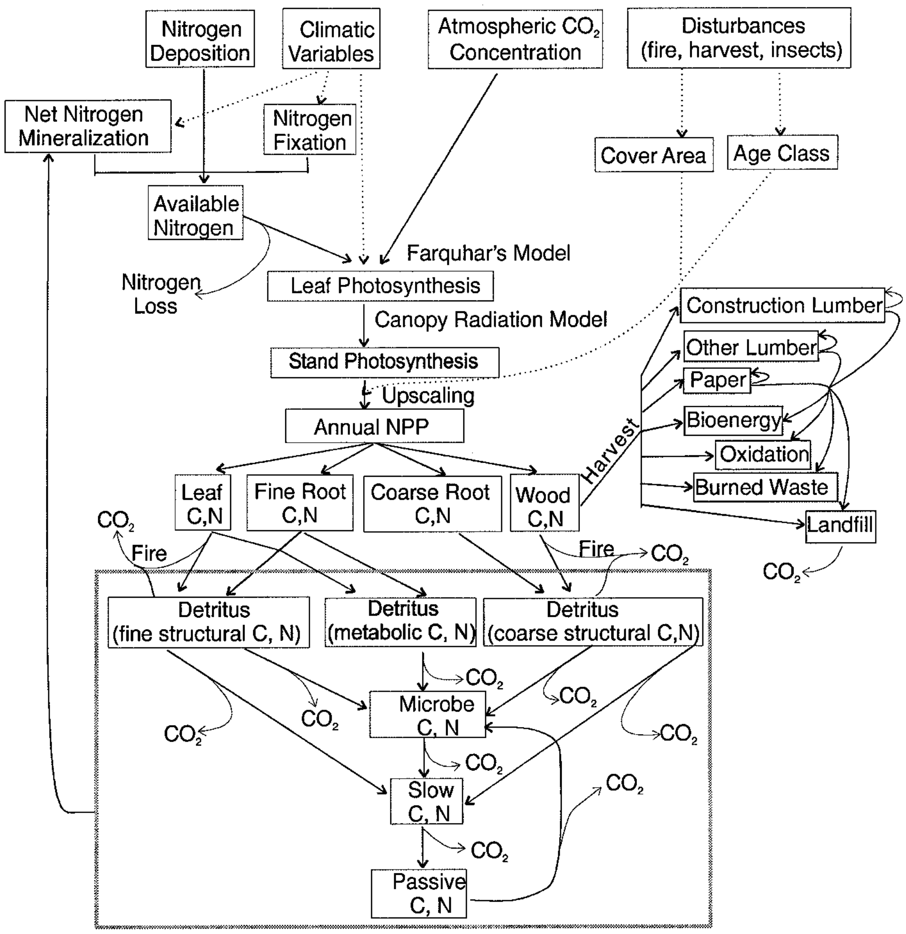

Figure 1. Flow chart of the integrated terrestrial ecosystem C-budget model (InTEC), which synthesizes the interacting effects of ecosystem disturbances, N deposition, climate change, and CO_2 fertilization on the C budget of boreal forests. Dashed arrows indicate influences, and solid arrows show C and N flows.

short-lived and 20% long-lived C pools (Kurz et al. 1992), with their turnover rates also listed in Table II.

TABLE I

Initial and secondary (includes recycling) partitioning coefficients for forest products in Canada (Kurz et al. 1992; Canadian National Forestry Database).

Initial partition	Secondary partition			
	Construction Lumber to	Other Lumber to	Pulp to	
Construction Lumber	0.236	0.05	/	/
Other Lumber	0.090	/	0.05	/
Pulp	0.225	/	/	0.05
Bioenergy	0.115	0.02	0.02	0.025
Burned as Waste	0.174	0.03	0.03	0.03
Oxidation	0.060	0.05	0.05	0.005
Landfill	0.100	0.85	0.85	0.90

TABLE II

Turnover rate and fossil fuel substitution efficiency of forest products in Canada (Kurz et al. 1992; Houghton 1993; Schlamadinger and Marland 1996).

	Turnover Rate (y^{-1})	Fossil Fuel Substitution efficiency
Construction Lumber	1/100	0.6
Other Lumber	1/40	0.6
Pulp	1/10	/
Short-lived Landfill	1/66.67	/
Long-lived Landfill	1/3000	/
Bioenergy	/	0.5

3. Simulation Experiments

3.1. Management Scenarios

Nagle (1990) estimated that approximately 7.2 Mha of marginal agricultural land and urban areas are available for afforestation in Canada. Although this estimate is disputable due to the vague definition of marginal agricultural land, we use the value because no other more credible estimate currently exists. The maximum area available for prompt reforestation following natural disturbance and harvesting will be the total area disturbed in the previous year.

The maximum acceptable N fertilization rate is considered to be that at which no N saturation may occur (i.e., annual N input should be below the critical N load). Measurements and modeling results (Dise and Wright 1995; Baron et al.

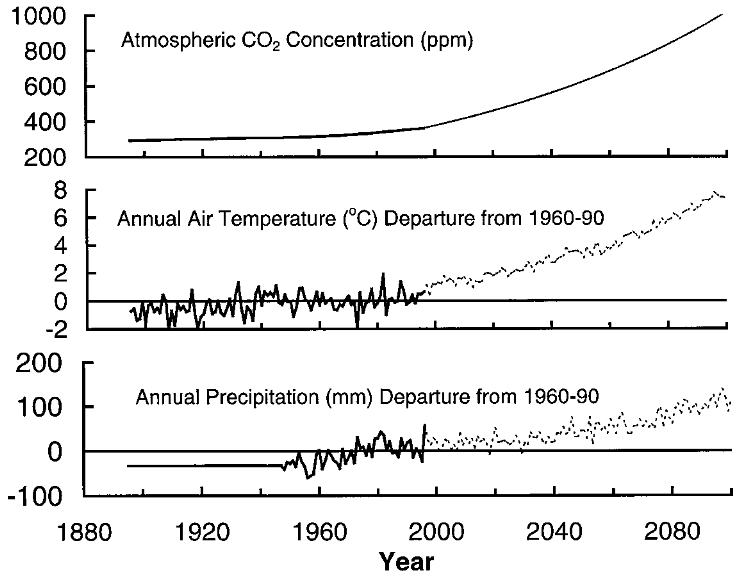

Figure 2. Measured (1895–1996, solid line) and predicted (1997–2100, dotted line) annual air temperature and precipitation departures from 1961–90 normals. Predicted values are simulation results from the first version of Canada's Coupled Global Model (CCGM1) using measured CO_2 concentration before present and 1% increase compounded annually afterwards (upper panel).

1994; Houle et al. 1997) suggest that the critical load is 10–19 kg N ha^{-1} y^{-1} for Canada's forest ecosystems. In comparison, the average atmospheric N deposition rate for Canada's forested area is 2.5 kg N ha^{-1} y^{-1} (Ro et al. 1995). These measurements indicate that an appropriate maximum N fertilization rate would be ~7.5 kg N ha^{-1} y^{-1}. To be conservative, we use two thirds of the latter value as the maximum N application rate in this study. Forest fertilization trials have shown that not all forest stands are suitable for N fertilization; semi-mature stands in the age range 20–90 years are generally more responsive (Foster and Morrison 1983; Weetman et al. 1987). About 40% of Canada's forests were within this age group in 1990 and ~60% in 1920 (Kurz and Apps 1998). Anticipating a possible fluctuation in the proportions of semi-mature stands in Canada's forests due to changes in disturbance rates, we therefore assumed that 30% of Canada's forests will be suitable for N application. Therefore, the maximum possible ('full-scale') implementation of low-rate N fertilization would be 5 kg N ha^{-1} y^{-1} to ~125 Mha semi-mature forests.

Forest harvest rates in recent years have been 20–30% below the annual allowable cut (Canadian National Forestry Database, www.nrcan.gc.ca/cfs). To assure long-term sustainability, the maximum allowable increase in harvesting level was therefore assumed to be 20%.

3.2. Climatic and Disturbance Scenarios

The Canadian Centre for Climate Modelling and Analysis (CCCMA) has recently developed its first coupled ocean–atmosphere GCM (the Canadian Global Coupled Model, CGCM1) (Flato et al. 1997). Under the IPCC IS92A 'business-as-usual' scenario, an increase of CO_2 at a rate of 1% per year (compounded) from the present until 2100 is used. The direct forcing effect of sulphate aerosols is also included (Boer et al. 1997). Figure 2 shows the simulation results of the CGCM1 for key Canadian annual climate statistics over the next century. Although CGCM1 reproduces present-day mean climate and its historical variation reasonably well, changes in future climate predicted by any GCM are clearly dependent upon the specification of GHG and aerosol forcing. Uncertainties in the future atmospheric concentrations of GHGs and aerosols lead to uncertainties in the projection of future climate. To circumvent this difficulty, a scenario approach is taken in this study. Since the CGCM1 results have not taken into account possible increases in C uptake by ecosystems and possible reductions in GHG emissions by the energy and end-use sectors, the actual radiative forcing due to atmospheric GHGs during the next century could be smaller than the 'business as usual' scenario. Therefore, we selected the CGCM1 simulation as the upper bound for the future (1997–2100) climate (dubbed 'scenario c1'). On the other hand, all GCMs predict that surface temperatures will increase at greater rates in the 21st century. Consequently, we selected climate data extrapolated using linear relationships derived from the historical period 1895–1996 as the lower bound for the future climate (dubbed 'scenario c2').

It has been suggested frequently that future disturbance rates due to wildfire and insect-induced mortality will increase under a warmer climate (Flannigan and Van Wagner 1991; Volney 1996; but see also Flannigan et al. 1998). Flannigan and Van Wagner (1991) predicted a possible 46% increase in seasonal fire severity rating for Canada under a $2 \times CO_2$ climate, indicating a similar projected increase in area burned. Bergeron and Flannigan (1995) found that mean fire intensity would likely decrease in eastern Canada, but increase in western Canada under a $2 \times CO_2$ climate. Yet, as with future climate, there is large uncertainty in these projections of future disturbance rates. As a result, a scenario approach is taken for future disturbance rates in this study. The average rate from pre-industrial times to the present (1996) is set as the lower bound ('scenario d1'), and double this average rate is set as the upper bound ('scenario d2'). We further assumed that in the baseline scenario, annual rates of harvesting and N-deposition would remain at current levels, as obtained from statistics for the period 1980–1996.

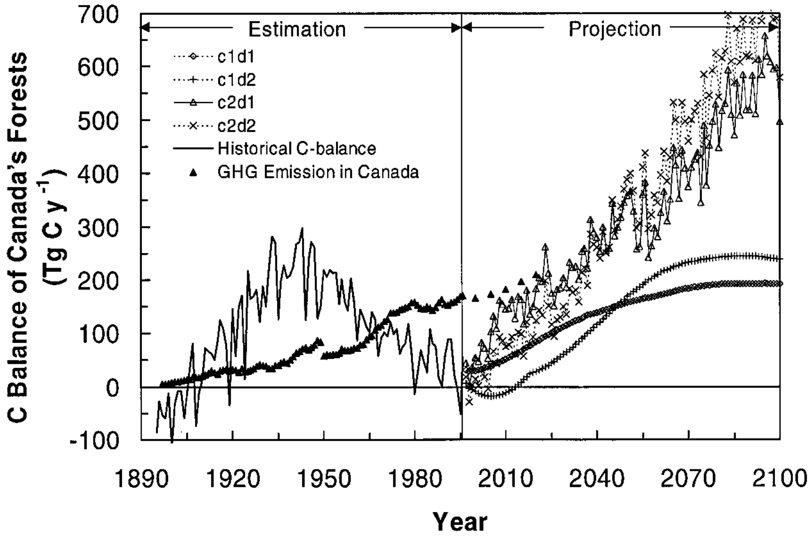

Figure 3. Baseline annual C balance projections for Canada's forests under four different scenarios: (1) low climate change rate and low disturbance rate (c1d1); (2) low climate change rate and high disturbance rate (c1d2); (3) high climate change rate and low disturbance rate (c2d1); and (4) high climate change rate and high disturbance rate (c2d2). Also included are historical annual C balance and Canada's observed and projected greenhouse gas (GHG) emissions from 1895 to 2020.

4. Results and Discussion

4.1. Baseline C Balance

Figure 3 shows estimated historical (1895–1996) and projected future (1997–2100) annual C balances of Canada's forests, respectively. Data sources of historical climate, N deposition, atmospheric CO_2 concentration, and disturbance rates (including forest fire, insect induced forest mortality, and harvesting) have been described previously (Chen et al. 1999d). According to the model, during the past 100 years, the country's forests underwent a period (1895–1905) as a small C source ($\sim$30 Tg C y^{-1}) due to large areas disturbed by fires and/or insects near the end of the 19th century, a period (1930–1970) as a large C sink ($\sim$170 Tg C y^{-1}) due to forest regrowth in previously disturbed areas, and a recent period (1980–1996) as a moderate C sink ($\sim$50 Tg C y^{-1}) (Chen et al. 1999d). The sink estimated for 1980–1996 is the net balance of the negative effects of increased disturbances and the positive effects of other non-disturbance factors. Analysis of the model output showed these non-disturbance factors, in order of importance, are (1) atmospheric N deposition estimated from data measured by the national monitoring network; (2) increased net N mineralization and fixation estimated from temperature and precipitation records; (3) CO_2 fertilization estimated from CO_2 records using the leaf-level photosynthesis model, and (4) increased growing season length, estimated from spring air temperature records. Increased disturbances (mostly fires and insects) in recent decades caused a loss of about 60 Tg C y^{-1} from the forests in 1980–1996. If disturbance rates had remained approximately constant during the period 1895–1996, Canada's forests in 1980–1996 would have been a sink of ∼150 Tg C y^{-1}. The large amount of C accumulated during 1930–1970 with relatively low disturbance rates contributed to larger than normal accumulations of decomposable organic material during and immediately following the period of disturbance – resulting in additional losses of ∼40 Tg C y^{-1} through decomposition in 1980–1996.

The projected C budgets for the next century suggest that for the approximate period 1997–2020, Canada's forests will remain a small sink, although the magnitude varies substantially under different scenarios. Under low disturbance rate scenarios (c1d1 and c2d1), the forests become a larger sink, but with a high disturbance rate and low climate change (c1d2), they could become a small C source. After the initial period ending ∼2020, Canada's forests could become an increasingly large C sink under all scenarios. This is due mainly to the relatively large fraction of the total forest area burned in the 1980s and 1990s entering a period of vigorous growth, combined with the positive effects on NPP of projected increases in growing season length and atmospheric CO_2 concentration, while the disturbance rate stabilizes. Such an outcome is, of course, dependent upon the stabilization of the disturbance regime. Figure 3, however, suggests that the long-term impacts of the disturbance regime are small compared to the effects of climate on NPP. Kurz and Apps (1995) found a similar trend in the annual C budget for Canadian boreal forests based on observed and projected changes in age-class distribution. The wide range in the magnitude of the projected sink, particularly beyond 2050, is a direct consequence of the uncertainties associated with the different scenarios. Hence it must be emphasized that any projection for Canada's future forest C-balance is subject to considerable uncertainty. The outcomes of these alternative scenarios should instead be treated as a range of possible baselines for comparing the C offset potentials of the different management strategies.

4.2. C Offset Potential of Afforestation in Canada

To estimate the C offset potential of afforestation in Canada, we made the following assumptions: (1) the ∼7.2 Mha urban and marginal agricultural lands available for afforestation (Nagel 1990) were carbon-neutral in the past and would remain so if not afforested (i.e., baseline projection in C balance is zero); (2) these lands have soil C densities similar to agricultural soils which on average contain ∼50% of that typically found in forest soils (Tarnocai 1997) and no significant woody biomass; (3) these lands will be planted with locally dominant tree species with similar success rate (71% using seedlings and 53% when grown from seed (Kuhnke and Brace 1986), causing established stands to grow at rates comparable to those of other forests in the same regions; (4) disturbances affect the afforested areas as they do all other forests, and the disturbed areas will be naturally regenerated. If these

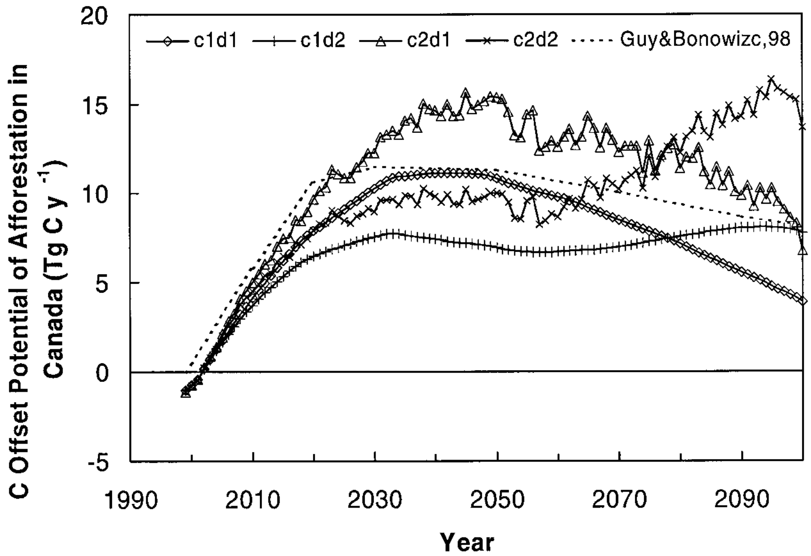

Figure 4. Estimated C offset potential of afforestation in Canada if all 7.2 Mha of available marginal agricultural land and urban areas are planted in 1999, under the four climatic and disturbance scenarios shown in Figure 3. Also plotted is an independent estimate of Guy and Benowicz (1998) for the same area.

lands were planted in 1999, they would release C in the initial 3 years, and then gradually increase C uptake to ~7 Tg C y^{-1} by 2030 under the low climate change and high disturbance scenario (c1d2), or to ~15 Tg C y^{-1} under the high climate change and low disturbance scenario (c2d1) (Figure 4). Increases in C uptake under the remaining scenarios (c1d1 and c2d2) are intermediate to these two values. The simulation shows a larger increase in C uptake under the c2 scenarios, because average growth rates are projected to be higher than those under c1 scenarios. On the other hand, a smaller increase in C uptake under higher disturbance conditions (d2 scenarios) is projected during the next century, except for the last 20 years when the higher disturbance rate would result in a younger and more productive age class.

These results are consistent with an independent estimate of Guy and Benowicz (1998) for the same available afforestation area, although the implementation details are somewhat different (Figure 4). They assumed that 28% of the area would be planted with hybrid poplars, and the remainder planted with species typical for the regions in which planting will occur. Cumulative C uptake includes above and below ground biomass plus increases in soil C for those areas where planting would occur on marginal agricultural land. For other regions, Guy and Benowicz assumed that soil C pools would not increase beyond the levels observed prior to afforestation. The effects of planting success, longer growing seasons, and disturbances were also not considered in their estimates.

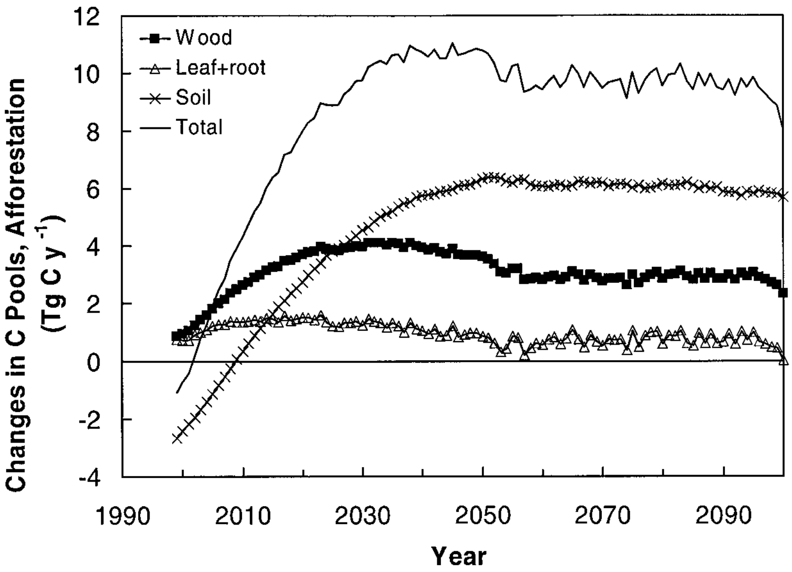

Figure 5. Estimated changes in the wood, root + foliage, and soil C pools resulting from full-scale afforestation in 1999 (i.e., of all 7.2 Mha of available marginal agricultural and urban land).

When averaged over the period 1999–2100 for all 4 climatic and disturbance scenarios, the approximate allocations of the increased C uptake to wood, roots + foliage and soil were 36%, 11% and 53%, respectively, (Figure 5). These partitioning coefficients are, however, not constant. For example, in the initial decade after afforestation, the soil C pool would undergo a net loss, whereas in the late 21st century, it would actually increase faster as the new forest approached maturity.

4.3. C OFFSET POTENTIAL OF PROMPT REFORESTATION IN CANADA

Figure 6 shows the projected C offset potential of prompt reforestation in Canada when carried out for the period 1999–2100. The area planted for the high disturbance scenarios (c1d2) and (c2d2) is about 1.8 times that planted under the low disturbance scenarios (c1d1) and (c2d1). The proportions of areas planted with seedlings and by direct seeding are assumed to remain at 93% and 7%, respectively (Canadian National Forestry Database, www.nrcan.gc.ca/cfs). While the typical delay period for natural regeneration in Canada's forests is in the range 1–10 years and has an average of ∼5 years (Bunce 1989), accelerated regeneration through planting and direct seeding can generally be carried out within a year of disturbance. Assuming all disturbed areas are planted, the additional C uptake maximizes around 2040, to 90–120 Tg C y^{-1} if disturbances occur at a high rate, or to 60–80 Tg C y^{-1} if disturbances occur at a low rate. The effects of climatic and disturbance scenarios on the C benefit of reforestation are similar to those of afforestation discussed above.

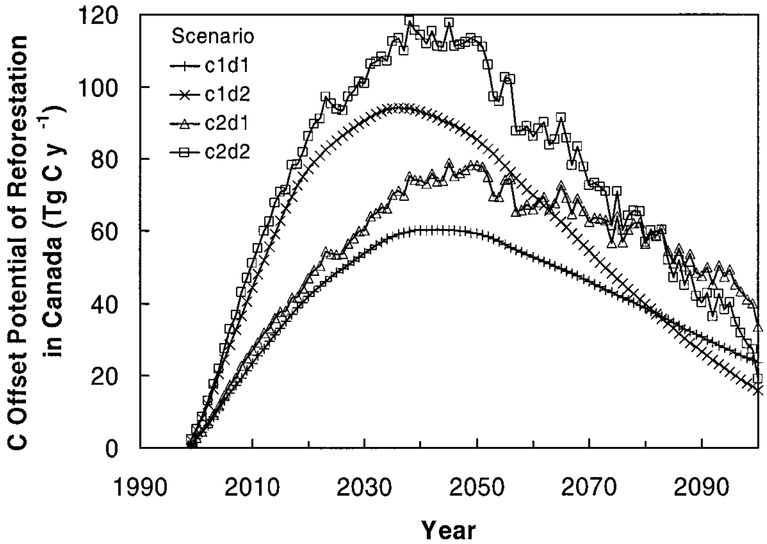

Figure 6. Estimated C offset potential resulting from prompt reforestation of all recently disturbed forest areas for the period 1999- 2100, under the four climatic and disturbance scenarios of Figure 3.

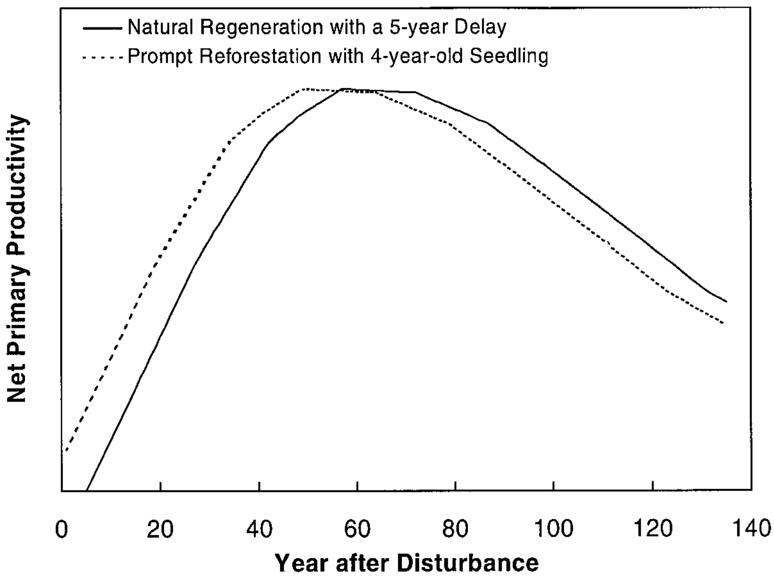

Figure 7. Estimated impacts of prompt reforestation on the relationship between net primary productivity and years following disturbance.

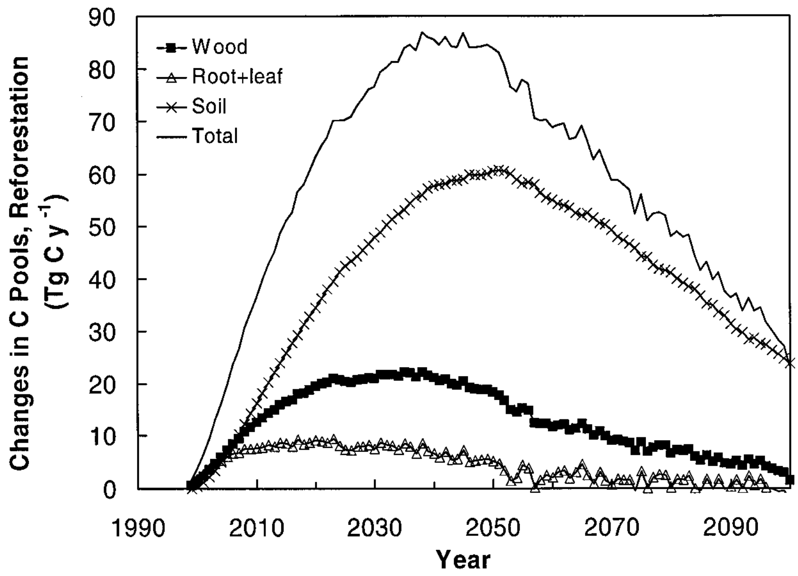

Figure 8. Same as Figure 5 except applied to the reforestation strategy.

When the full life cycle of a forest stand is considered, the increase in C uptake due to prompt reforestation can be viewed as the result of eliminating the 5-year natural regeneration delay period during which annual NPP was not contributing significantly to C sequestration (Auclair and Carter 1993), while soil respiration remains high (Burke and Zepp 1997). Yet, the duration of this natural regeneration delay may vary significantly depending on location, species and, site conditions. Consequently, different natural regeneration delay lengths have been reported and used (Kurz and Apps 1995; DesRochers and Gagnon 1997). Kurz and Apps (1995) used a 10-year natural regeneration delay, whereas DesRochers and Gagnon (1997) reported that major boreal forest species may be naturally regenerated in 1–3 years. Hence, the 5-year delay assumed for this study appears to be a reasonable estimate of the median value. An additional effect of prompt regeneration is a forward shift of the stand growth curve, which also influences the C offset potential (Figure 7). Over the decades following reforestation, the early arrival of higher growth rates as the stand matures will increase mean annual C uptake, although this advantage could be reversed if stands are allowed to become overmature. This age-related dynamic explains the relatively rapid projected increase in C uptake due to reforestation during 1999–2040, and the decrease in subsequent decades.

For the projected increases in C uptake created by reforestation, the additional accumulations in the wood, roots + foliage and soil C pools, were about 22%, 8% and 70% respectively, when averaged over the period 1999–2100 for the four climatic and disturbance scenarios (Figure 8).

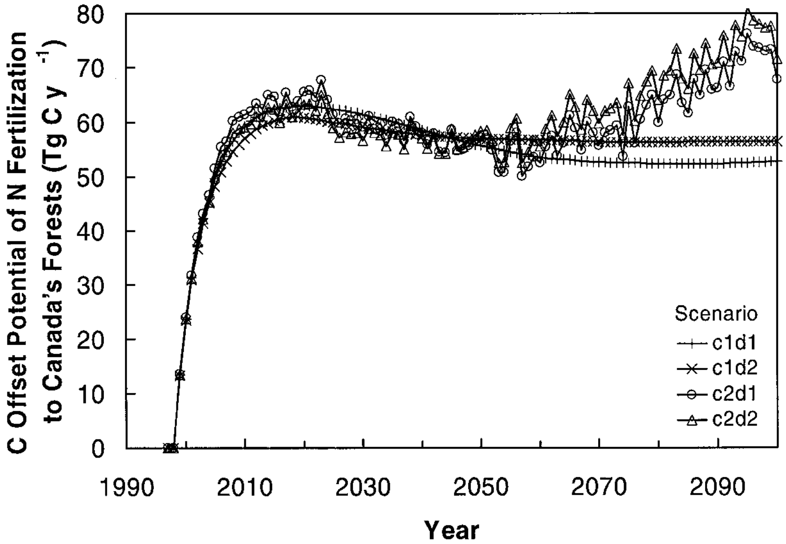

Figure 9. Estimated C offset potential of low-rate N fertilization in Canada when 5 kg N ha^{-1} y^{-1} is applied to ~125 Mha of semi-mature forest stands (i.e., the maximum area considered possible for this strategy) during 1999–2100, under four different climatic and disturbance scenarios.

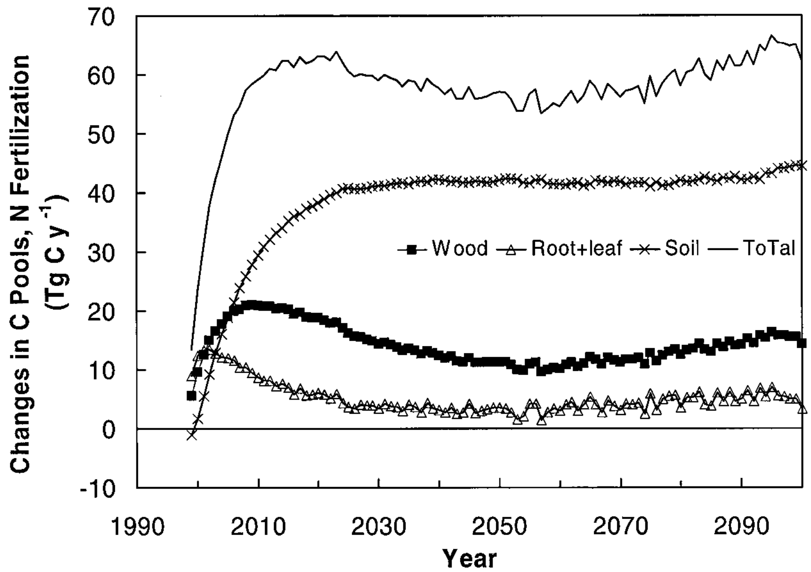

Figure 10. Same as Figure 5 except applied to the low-rate N fertilization strategy.

4.4. Potential of Low-rate N Fertilization to Increase C Uptake by Canada's Forests

Application of 5 kg N $ha^{-1}y^{-1}$ during 1999–2100 to the 125 Mha of semi-mature forests (∼30% of Canada's forest area) would increase C uptake to ∼60 Tg C y^{-1} by 2010 and beyond (Figure 9). The differences in response to this treatment among the different climatic and disturbance scenarios are small. Averaging over the whole period 1999–2100, the estimated N fertilization efficiency is ∼80 kg C $(kg\ N)^{-1}$. About 25% of increased C uptake ends up in the wood C pool, ∼9% goes to roots + foliage, and the remaining 66% accumulates in the soil pool (Figure 10). This partitioning is almost identical to that reported by Kurz and Apps (1998), who found that total biomass C in Canada's forests increased from 11.0 Pg to 14.5 Pg from 1920 to 1989, while the soil C pool increased from 61.2 Pg to 71.4 Pg; i.e., ∼34% of the total increase accumulated in forest biomass. Since only ∼25% of the increase in C uptake accumulates in wood, the N fertilization efficiency for wood alone is thus ∼20 kg C $(kg\ N)^{-1}$.

One question that then arises is whether there is experimental evidence to support this projection. A number of fertilization trials were conducted in Canada during 1960s–80s, and their results can be used as a validation (Weetman et al. 1987). One of the most comprehensive N fertilization experiments in Canada was the Interprovincial Forest Fertilization Program (IFFP) (Weetman et al. 1987). The IFFP field trials were designed to test the effect of N when applied as urea at rates of 112 and 224 kg ha^{-1} on the growth of pole-size and semi-mature stands. All provinces except Newfoundland, British Columbia, and Prince Edward Island participated in the program. The IFFP comprised 81 standard trials in stands of jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* [Mill.] B.S.P), red spruce (*Picea rubens* Sarg.), white spruce (*Picea glauca* [Moench] Voss), balsam fir (*Abies balsamea* [L.] Mill), and trembling aspen (*Populus tremuloides* Michx.) from 1969 to 1972. Seventy-five installations were remeasured after 10 years. Figure 11 shows the N fertilization efficiency expressed in units of kg wood C increment per kg N applied. A conversion factor of 200 kg C m^{-3} wood is used here to convert the results of these field trials from volume to C mass terms. The trial results indicate N fertilization efficiencies in the range 3.4–18 kg wood C $(kg\ N)^{-1}$ at an application rate of 224 kg N ha^{-1}, compared to 7.6–18 kg wood C $(kg\ N)^{-1}$ when applied at 112 kg N ha^{-1}. In another experiment, where 56 kg N ha^{-1} were applied six times over 12 years, with stand remeasurement after 22 years, Weetman et al. (1995) reported N fertilization efficiency of 39.4 kg wood C $(kg\ N)^{-1}$. With single application and remeasurement after 5 years, Morrison et al. (1976) observed an N fertilization efficiency of 8.2 kg wood C $(kg\ N)^{-1}$ for an application rate of 56 kg N ha^{-1}, compared to 2.2 kg wood C $(kg\ N)^{-1}$ at 448 kg N ha^{-1}. All these results show greater N fertilization efficiency at lower application rates, as predicted by the InTEC model. Ballard (1984) developed a simple empirical model for predicting stand volume growth response to fertilization which estimates cumulative stand volume growth response (*V*) from:

$$V = KTACZQ, \quad (5)$$

where *K* is a constant (= 52.76 m^3 ha^{-1} for N application to coastal Douglas-fir), *T* is a dimensionless factor accounting for the period after application (= 0.97 after 10 years), *A* is the application rate factor (= 1- exp(–0.0089*r*), where *r* is the application rate in kg N ha^{-1}), *C* is a stand composition factor accounting for the fraction of responding species (= 1 for virtually pure stands), *Z* is a stocking factor (= $0.02417s – 0.0001778s^2$, where *s* is stocking in unit of percentage of the normal), and *Q* is a site factor (= 1.9877 – 0.0394*q*, where *q* is the 50-year site index in metres). This simple empirical model described measured responses of Douglas-fir to N fertilization (Anonymous 1982; Barclay and Brix 1985), which are much greater than most other species (Figure 11). Overall, despite the fact that forest growth responses to N fertilization are extremely variable, these results provide some experimental evidence that N fertilization could significantly increase average C storage in forest biomass. The responses calculated by InTEC lie well within the range of N fertilization efficiencies obtained in these fertilization trials.

It must be emphasised, however, that the general application of these experimental results on a wide scale is extremely dubious: the response of particular sites to applications of N fertiliser are generally not well-understood, and hence the predictions of increased productivity at other sites are subject to considerable uncertainty.

4.5. C Offset Potential of the Substituting Fossil Fuel with Wood Strategy

Figure 12 shows the C offset potential of increasing forest harvesting and using the extra harvested material as a substitute for fossil fuels, both directly and indirectly from 1999–2100. With full-scale application, harvesting would be increased by 20% compared to current annual average rates. Direct substitution of fossil fuel implies conversion to bioenergy of 90% of wood currently burned as waste (i.e., with no energy capture), and 100% of the pulp fraction of the extra harvested products (Table I). Table I shows that the percentage of wood burned-as-waste is substantial (17.4%). If 90% of this material was instead substituted for fossil fuels, with an efficiency of 0.5 (i.e., 1 mg wood C replaces 0.5 mg fossil C), fossil C emissions would be reduced by ∼3.27 Tg C y^{-1}. Indirect substitution assumes that the lumber fraction of the extra harvested products is used to replace steel, aluminum, plastics and concrete, whose production would have released a large amount of fossil carbon. The efficiencies of these indirect substitutions vary with the types and lifespans of wood products and the materials for which they are substituted (Nabuurs 1996). For example, substituting concrete sleepers with oak, carpet (polyamide) with oak parquet, and plastic (polythylene) palettes by

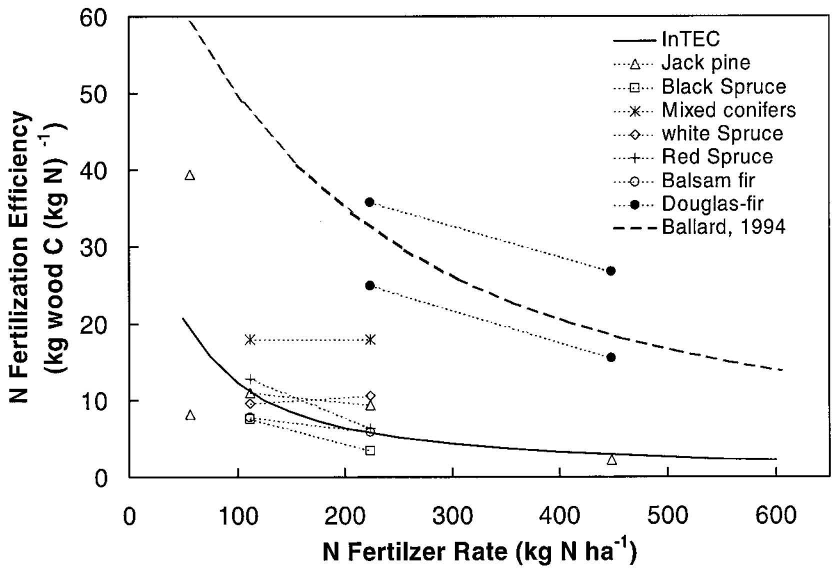

Figure 11. N fertilization efficiency estimated 10 years after N fertilizer application in the Inter-provincial Forest Fertilization Program (Weetman et al. 1987). Stands of jack pine, black spruce, mixed conifers (mainly black spruce and jack pine), white spruce, red spruce, and balsam fir, were treated at 81 sites across Canada with application rates of 112 and 224 kg N ha^{-1}. To supplement these data, we also include jack pine results remeasured after 5 years for application rates of 56 and 448 kg N ha^{-1} (Morrison et al. 1976), jack pine results remeasured after 22 years at an application rate of 56 kg N ha^{-1} repeated six times over 12 years (Weetman et al. 1995), and Douglas-fir results remeasured after 12 years at application rates of 224 and 448 kg N ha^{-1} (Anonymous 1982; Barclay and Brix 1985). Simulation results from InTEC and a simple empirical model of Ballard (1984) are also presented for comparison.

spruce, reduces C emission by 0.6, 1.0, and 0.3 mg per mg C of wood, respectively (Nabuurs 1996). On average, the fossil fuel substitution efficiency for construction and other lumbers is assumed to be 0.6 (Table II), following Nabuurs (1996) and Schlamadinger and Marland (1996). Because fossil fuel substitutions at current levels have been incorporated in the national GHG emission statistics, we account only for these simulated extra replacements and the resultant reductions in fossil C emissions. This strategy creates an almost steady C offset potential of $\sim$10 Tg C y^{-1} during 1999–2100, when the impact of the strategy on ecosystem C pools is excluded (i.e., only fossil fuel substitution, forest product C pool, and landfill C pools are considered). The increased harvesting would reduce both the forest ecosystem C pools and forest productivity in the initial decades. Consequently, when all C pools and the fossil fuel substitution benefit are considered in total, this strategy would have little benefit in the initial decades (Figure 12). As the harvested areas regenerate and regrowth increases, however, a relatively large C benefit would be expected to accrue in the second half of the 21st century.

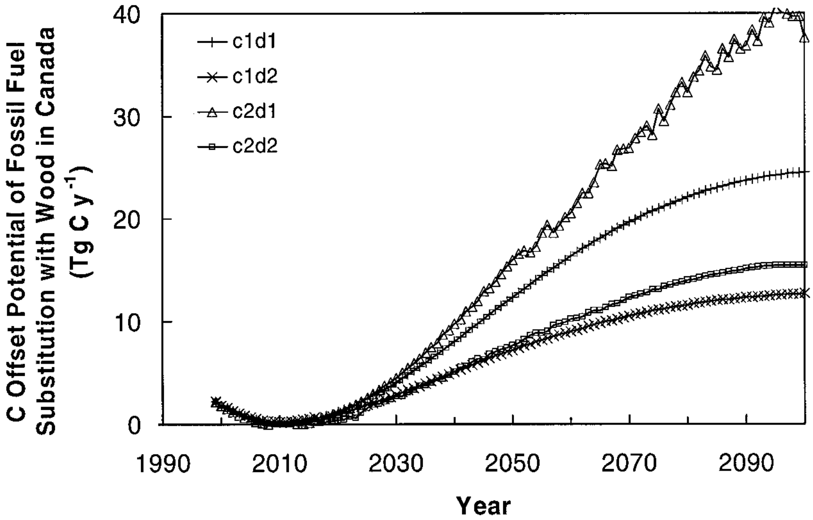

Figure 12. Estimated C offset potential of increasing annual forest harvesting by 20% above current levels for the period 1999–2100 and using the extra wood products as biofuels to substitute for fossil fuels, under the four climatic and disturbance scenarios of Figure 3.

4.6. Carbon Cost of These Forest Management Options

The C costs associated with afforestation and reforestation (mainly fossil fuel consumed in transporting seedlings, personnel and equipment) are typically much lower than those for harvesting. Schlamadinger and Marland (1996) reported that the typical C cost for harvesting is 0.01 Mg C of fossil fuel per Mg C of wood harvested, which corresponds to an average release of approximately 0.47 Mg C y^{-1} per hectare of harvested area. To be conservative, we made the assumption that afforestation and reforestation (including seed collection, seedling cultivation, and site preparation) would release as much as 50% of the fossil C emissions due to harvesting a similar area. Hence, carrying out afforestation of 7.2 Mha would incur an estimated total C cost of ~3.38 Tg C, or ~0.4% of the cumulative C benefit from 1999–2100 under the c1 scenarios. The C cost of implementing the reforestation strategy at full scale would be ~0.96 Tg C y^{-1}, or ~2.0% of the mean additional C uptake of 47.9 Tg C y^{-1} under the d1 scenarios (i.e., prompt reforestation of 4.07 Mha y^{-1}). Under the d2 scenarios (i.e., prompt reforestation of 7.25 Mha y^{-1}), the cost would increase to 1.7 Tg C y^{-1}, or ~2.6% of the mean additional C uptake of 66.3 Tg y^{-1}.

For the N fertilization program, the major C costs are caused by N fertilizer production and its repeated application to the vast area of forest. In 1993, about 2.6 Tg nitrogen fertilizer, 0.32 Tg P_2O_5 phosphate fertilizer, and 6.67 Tg K_2O potassium fertilizer were produced in Canada (Korol and Girard 1994). Total fossil fuel C emission for producing these fertilizer was approximately 0.72 Tg (Nyboer and Bailie 1997; Natural Resources Canada 1997). Clearly less fossil fuel would be consumed if only N fertilization were carried out. On the other hand, to balance the nutrition requirements of some forest sites, sulphur and potassium fertilizers may also need to be applied. Therefore, to be conservative, we estimate the C cost of N fertilizer production to be 0.72 Tg C fossil fuel for the 2.6 Tg N nitrogen fertilizer produced, i.e., 0.28 Tg C $(\text{Tg N})^{-1}$. The fuel consumption rates of a small fixed-wing aircraft or a helicopter range from 0.1 to 5 km flight distance per 1 kg aviation fuel, with a mean value of $\sim$1 km per 1 kg aviation fuel. Using the mean fuel consumption rate and assuming a spread width of 30 m, we calculate that to apply 5 kg N fertilizer over 1 ha forest area would require flying 0.333 km, and consume 0.5 kg aviation fuel. Combustion of 1 kg aviation fuel emits 0.76 kg C, including the CO_2 equivalents of methane (CH_4) and nitrous oxide (N_2O) (Natural Resources Canada 1997). Therefore, the C cost of applying N fertilizer would be $\sim 0.333 \times 0.76$ kg C per 5 kg N of nitrogen fertilizer, i.e., 0.05 Mg C $(\text{Mg N})^{-1}$. Considering the extra fuel consumption needed to fly to the application site, the possible need for applying other supplemental fertilizers, and the C cost of ground transportation of fertilizer, we allow a doubling of the total C cost of N fertilizer application to 0.10 kg C $(\text{kg N})^{-1}$. The estimated C cost of N fertilization (i.e., including production, transport, and application) is then 0.38 kg C per 1 kg N applied, and a total of 0.24 Tg C y^{-1} for applying 5 kg N $ha^{-1}y^{-1}$ over the 125 Mha forest area. As discussed in section 4.4, applying 1 kg N fertilizer would increase uptake by $\sim$80 kg C y^{-1}. Therefore, the estimated C cost of low-rate N fertilization would be 0.38 kg C fossil fuel per 80 kg increase in C uptake, or $\sim$0.5%.

The C costs of harvesting and processing bioenergy products are assumed to be 0.01 Mg C of fossil fuel (Mg C of wood harvested)$^{-1}$, and 0.05 Mg C of fossil fuel (Mg C of wood processed)$^{-1}$, respectively, based on data for the USA (Schlamadinger and Marland, 1996). The C cost for increasing the harvest rate by 20% to substitute fossil fuel would be 0.54 Tg C y^{-1}, or 5.3% of the mean C benefit created by increasing the harvest to substitute for fossil fuels during 1999–2100.

4.7. Comparison with Other GHG Emission Reduction or C Uptake Enhancement Programs

The National Action Program on Climate Change (NAPCC) is Canada's response to the United Nations Framework Convention on Climate Change (FCCC) (Environment Canada 1997). The NAPCC program includes GHG emission reduction initiatives announced or planned by the fossil fuel, electricity, non-energy, and end-use (i.e., residential, commercial, industry, and transportation) sectors (Environment Canada 1997; Natural Resources Canada 1997). If all NAPCC initiatives were adopted, it is estimated that they would reduce GHG emissions by 10–29 Tg C y^{-1} during the period 2000–2020 (Figure 13). In comparison, the combination of the four alternative forest management strategies studied here could have a net C offset potential (i.e., C offset potential – C cost) between 23 ± 8 and 129 ± 59 Tg C y^{-1} in the same period. The uncertainties shown here are estimated from two error

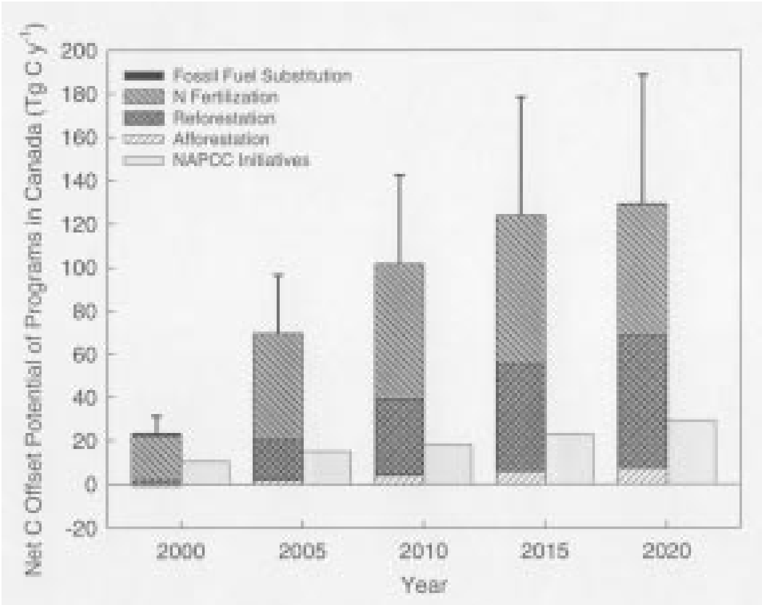

Figure 13. Comparison of net C offset potential (i.e., C offset potential – C cost) of the four alternative forest strategies combined and the Canadian National Action Program on Climate Change (NAPCC) initiatives. Error bars show the sum of one standard deviation of C offset potentials under different scenarios plus 25% of the mean potential of each strategy to accounting for the uncertainty in NPP estimation.

sources. One is the difference in C offset potentials under different climatic and disturbance scenarios; one standard deviation is assumed for this type of uncertainty. The other is uncertainty in NPP estimation. In a previous study (Liu et al. 1997), we estimated that the accuracy of annual mean NPP of Canada's forests is within 25%. With the historical change approach implemented in InTEC, C offset potentials can also be estimated to $\pm$ 25% (Chen et al. 1999a). The error bars in Figure 13 show the sum of the two uncertainties. When each individual strategy is considered, afforestation, reforestation, N fertilization, and fossil fuel substitution with wood contribute 4, 37, 59, and 0%, respectively, to the combined net C offset potential during 1999–2020.

By implementation of appropriate management practices – including increased input of crop residues, reduced tillage, and restoration of marginal soils, agricultural management practices may serve as an additional means of mitigating GHG emissions (Cole et al. 1996). Table III provides estimates of the C balance of agricultural soils in Canada from 1990 to 2010 (Environment Canada 1997). The projected increase in C storage in Canada's agricultural soils during this period occurs mainly because of anticipated increases in the use of non-tillage practices and reductions in summer-fallow (Smith et al. 1997). Table III shows that this projected increase, relative to 1990 levels, ranges from 2.1 to 2.5 Tg C y^{-1}. Ideally, the

TABLE III

Projected carbon balance and increase in C uptake by agricultural soils in Canada (Environment Canada 1997). Positive and negative budget values indicate net C sink (uptake from atmosphere) and source (release to atmosphere), respectively.

Year	1990	1995	2000	2005	2100
C Budget (Tg C y^{-1})	–1.91	–0.76	0.20	0.52	0.50
Increase in C Uptake from 1990 (Tg C y^{-1})	0.00	1.14	2.1	2.43	2.40

increase in C uptake through agricultural practices should be determined relative to baseline projections, for which no new agricultural practices are implemented. Because the C loss decreases gradually after the land was first converted to agricultural use, using 1990 as the baseline projection may slightly overestimate the C benefit of agricultural practices (Smith et al. 1997). Yet, even if we use these values as the additional C uptake that could be achieved, they are an order of magnitude smaller than the combined net C benefit of the four alternative forest management strategies presented here. Such a difference is not unexpected, considering that agricultural land covers approximately one tenth the area of Canada's forest (Smith et al. 1997), and that the C content of forest ecosystems is, on average, double that of agricultural soils (Tarnocai 1997). In addition, the residence time of C in forest ecosystems is typically longer than in agricultural soils because forest ecosystems produce slowly-decomposing, coarse-woody materials that are absent in agricultural ecosystems.

5. Concluding Remarks

The C offset potentials and costs of four alternative management strategies which could theoretically be applied on a large scale to Canada's forest resources during the 21st century were investigated using an Integrated Terrestrial Ecosystem C-budget model (InTEC). The four management strategies considered were afforestation, reforestation, nitrogen (N) fertilization at low-rates, and increasing the harvest of wood to substitute for fossil fuel. The InTEC model was modified to account for the effects of landfills, wood products recycling, and fossil fuel substitution in the C budget.

Afforestation of all available ~7.2 Mha of marginal agricultural land and urban land in 1999 would yield an average C benefit of ~8 Tg C y^{-1} during 1999–2100. Similar results were reported by Guy and Benowicz (1998). Prompt reforesting of all recently disturbed areas would have an average C benefit of ~57 Tg C y^{-1}. The upper limit of the N fertilization strategy was set so that most suitable forest stands would be fertilized but N saturation would not occur. Based on N critical load studies, N deposition measurements, and N fertilization trials, we set the upper limit of the N fertilization strategy to be 5 kg N ha^{-1} y^{-1} applied to ∼125 Mha semi-mature stands. If fully implemented, this strategy would create an average C benefit of ∼58 Tg C y^{-1} during 1999–2100. The responses estimated in this study lie well within the range of N fertilization efficiencies obtained in extensive N fertilization trials conducted across boreal Canada during 1960–90. Since forest harvesting rates in recent years have been ∼20–30% below the annual allowable cut, we assumed that harvesting wood biofuel would be fully sustainable if the increased harvesting were limited to 20% above current rates. Again, if fully implemented, this strategy would produce an average ∼11 Tg C y^{-1} benefit during 1999–2100.

Considering only the next two decades (1999–2020), the C offset potential would be 3.6, 32, 51, and 0.1 Tg C y^{-1}, for the afforestation, reforestation, low-rate N fertilization, and fossil fuel substitution with wood strategies, respectively – if these strategies were implemented at full scale.

Overall, low-rate N fertilization appears to have the largest C benefit potential, although it also has the least certainty of success. Considerable research effort will be required to determine the true potential C gains from a fertilisation program carried out on the scale envisaged here. A program to ensure consistent prompt reforestation of recently disturbed stands would create large C benefit potential in the time frame of decades to a century, although the benefits would likely decrease over longer periods. Afforestation and increasing harvesting to use the extra wood products for fossil fuel substitution have relatively limited short-term C benefit potentials, but their benefits should increase in the longer term.

Afforestation and low-rate N fertilization appear to be the most C cost efficient options to increase C uptake by Canada's forests with C cost/benefit ratios of 0.4% and ∼0.5%, respectively, followed by prompt reforestation of disturbed areas at 2.0–2.6%, while the fossil fuel substitution with wood strategy would be the least C cost efficient at 5.3%.

If implemented to the fullest extent possible from 1999–2020, the four alternative forest management strategies combined would create a potential net C benefit of 23 ± 8–129 ± 59 Tg C y^{-1} during 1999–2020. This is 2–7 times the estimated total potential GHG emission reduction that could be achieved through implementation of NAPCC initiatives during 2000–2020. The potential is also an order of magnitude larger than the potential increase in C uptake due to improved agricultural practices in Canada during 2000–2010.

Finally, we emphasize that this study was a first attempt to estimate C offset potentials and costs of four alternative forest management strategies in Canada. We have not attempted to evaluate the technical or socio-economic constraints of these strategies. To assess their feasibility would require detailed knowledge of factors such as site accessibility, availability of materials (including seedlings, seed, and N fertilizer), availability of transportation and implementation techniques, and so on. Potential socio-economic constraints include economic benefits and costs, as well as positive and negative impacts on other forest uses (e.g., food, wood supply and fuelwood production; relaxation and recreation; wildlife habitat; watershed management). In addition, implementation of a fertilization program on the scale envisaged here may raise significant ethical and ecological questions that can only be answered with much public debate. It would also be necessary to compare the potential C benefits of implementing these strategies with those derived from competing programs with the same C offset objective.

Clearly, this study cannot answer many of these important questions. Nevertheless, it does offer a first broad-scale estimate of the C offset potentials of four forest management strategies widely considered in Canada, upon which assessments of technical feasibility and socio-economic constraints can be built. Only after comprehensive feasibility studies have been completed, and the results obtained in this study validated, should a decision-maker determine whether any of these strategies should be implemented and at what scale.

Acknowledgments

Funding for this project is provided by CCRS (Canada Centre for Remote Sensing) and PERD (Panel for Energy Research and Development, Canada). The invaluable assistance of and discussion with several individuals made this research possible: Robert Stewart, Alan Barr, Mike Novak, Andy Black, Ted Hogg, Barbara Kishchuk, and Leonard Brown. Pierre Bernier, Ole Hendrickson, Mike Lavigne, and Sylvain Leblanc internally reviewed an early version of this manuscript, and their criticisms have greatly benefited this manuscript. We thank two anonymous reviewers for their thoughtful comments on the manuscript.

References

Anonymous: 1982, *Regional Nutrition Research Project. Biennial Report 1980–1982*, Seattle, WA, University of Washington, College of Forest Resources, Institute of Forest Resources, Contrib. No. 46.

Auclair, A.N.D. and Carter, T.B.: 1993, 'Forest wildfire as a recent source of CO_2 at northern latitudes', *Can. J. For. Res.* **23**, 1528–1536.

Ballard, T.M.: 1984, 'A simple model for predicting stand volume growth response to fertilization application', *Can. J. For. Res.* **14**, 661–665.

Barclay, H.J. and Brix, H.: 1985, *Fertilization and Thinning Effects on a Douglas-fir Ecosystem at Shawnigan Lake: 12-year Growth Response*, Can. For. Serv., Inf. Rep. BC-X-271.

Baron, J.S., Ojima, D.J., Holland, E.A. and Parton, W.J.: 1994, 'Analysis of N saturation potential in Rocky Mountain tuntra and forest: Implications for aquatic systems', *Biogeochemistry* **27**, 61–82.

Bergeron, Y. and Flannigan, M.D.: 1995, 'Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest', *Water, Air, and Soil Pollut.* **82**, 437–444.

Boer, G.J., Flato, G.M., Reader, M.C. and Ramsden, D.: 1997, 'Transient climate change simulation with historical and projected greenhouse gas and aerosol forcing', unpublished.

Bonan, G.B.: 1995, 'Land-atmosphere CO2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model', *J. Geophys. Res.* **100**, 2817–2831.

Brown, S. et al.: 1996, 'Management of forests for mitigation of greenhouse gas emissions', in R.T. Watson et al. (eds.), *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, Cambridge, Cambridge University Press, pp. 775–794.

Bunce, H.: 1989, *The Level of Not Satisfactorily Restocked Forest Lands in Canada*, Forestry Canada.

Burke, R.A., Zepp, R.G., Tarr, M.A. and Miller, W.L.: 1997, 'Effect of fire on soil-atmosphere exchange of methane and carbon dioxide in Canadian boreal forest sites', *J. Geophys. Res.* **102**, 29289–29300.

Canadian Forest Service: 1998, *The State of Canada's Forests*, Ottawa, ON, Canadian Forest Service.

Chen, W.J., Chen, J.M., Liu, J. and Cihlar, J.: 1999a, 'Approaches for reducing uncertainties in regional forest carbon balance', *Global Biogeochem. Cycles* (in press).

Chen, W.J., Black, T.A., Yang, P.C., Barr, A.G., Neumann, H.H., Nesic, Z., Novak, M.D., Eley, J. and Cuenca, R.: 1999b, 'Effects of climate variability on the annual carbon sequestration by a boreal aspen forest', *Global Change Biology* **5**, 41–53.

Chen, J. M., Liu, J., Cihlar, J. and Goulden, M.L.: 1999c, 'Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications', *Ecological Modeling* (in press).

Chen, J.M., Chen, W.J., Liu, J., Cihlar, J. and Gray, S.: 1999d, 'Annual carbon balance of Canada's forests during 1895–1996', *Global Biogeochem. Cycles* (in press).

Cole, V. et al.: 1996, 'Agriculture options for mitigation of greenhouse gas emissions', in R.T. Watson, et al. (eds.), *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, Cambridge, Cambridge University Press, pp. 747–766.

DesRochers and Gabnon: 1997, 'Is ring count at ground level a good estimate of black spruce age?' *Can. J. For. Res.* **27**, 1263–1267.

Dise, N.B. and Wright, R.F.: 1995, 'N leaching from European forests in relation to N deposition', *For. Ecol. Man.* **71**, 153–161.

Dixon, R.K (ed.): 1997, 'Climate change impacts and response options in Eastern and Central Europe', *Climate Change* **36**, 1–232.

Environment Canada: 1997, *Canada's Second National Report on Climate Change*, Environment Canada.

Farquhar, G.D., von Caemmerer, S. and Berry, J.A.: 1980, 'A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species', *Planta* **149**, 78–90.

Flannigan, M.D. and van Wagner, C.E.: 1991, 'Climate change and wildfire in Canada', *Can. J. For. Res.* **21**, 66–72.

Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M.: 1998, 'Future wildfire in circumboreal forests in relation to global warming', *J. Veg. Sci* **9**, 469–476.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader and M.C., Weaver, A.J.: 1997, 'The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate', unpublished.

Foster, N.W. and Morrison, I.K.: 1983, *Soil Fertility, Fertilization, and Growth of Canadian Forests*, Can. For. Serv., Inf. Rep. O-X-353.

Goulden, M.L., Wofsy, S.C., Harden, J.W., Trumbore, S.E., Crill, P.M., Gower, S.T., Fries, T., Daube, B.C., Fan, S.-M., Sutton, D.J., Bazzaz, A. and Munger, J.W.: 1998, 'Sensitivity of boreal forest carbon balance to soil thaw', *Science* **279**, 214–217.

Guy, R.D. and Benowicz, A.: 1998, *Can Afforestation Contribute to a Reduction in Canada's Net CO_2 Emissions*? Montreal, PQ, Canadian Pulp and Paper Association.

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harries, N., Kattenberg, A. and Maskell, K. (eds): 1996, *Climate Change 1995: The Science of Climate Change*, Cambridge, Cambridge University Press.

Houghton, R.A.: 1993, 'Is C accumulating in the northern temperate zone?' *Global Biogeochem. Cycles* **7**, 611–617.

Houle, D., Paquin, R., Camira, C., Ouimet, R. and Duchesne, L.: 1997, 'Response of Lake Clair Watershed (Duchesney, Quebec) to changes in precipitation chemistry (1988–1994)', *Can. J. For. Res.* **27**, 1813–1821.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. and Wigley, T.M.L.: 1996, 'Climate Models-projections of future climate', in J.T. Houghton et al. (eds.), *Climate Change 1995: The Science of Climate Change*, Cambridge, Cambridge University Press, pp. 285–357.

Korol, M. and Girard, L.: 1994, *Canada Fertilizer Consumption, Shipments and Trade 1992/93*, Farm Input Market Unit, Farm Policy and Programs Directorate, Agriculture and Agri-Food Canada.

Kuhnke, D.H. and Brace, L.G.: 1986, *Silviculture Statistics for Canada, 1975–76 to 1982–83*, Can. For. Serv., Inf. Rep. NOR-X-275.

Kurz, W.A. and Apps, M.J.: 1995, 'An analysis of future C budgets of Canadian boreal forests', *Water, Air, and Soil Pollution* **82**, 321–331.

Kurz, W.A. and Apps, M.J.: 1998, 'A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector', *Eco. Appl.* (accepted).

Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J.: 1992, *The C Budget of the Canadian Forest Sector: Phase I. Forestry Canada*, Can. For. Serv., Inf. Rep. NOR-X-326.

Liu, J, Chen, J.M., Cihlar, J. and Park, W.M.: 1997 'A process-based boreal ecosystem productivity simulator using remote sensing inputs', *Remote Sens. Environ.* **62**, 158–175.

Lloyd, J. and Taylor, J.A.: 1994, 'On the temperature dependence of soil respiration', *Functional Ecology* **8**, 315–323.

Luo, Y., Sims, D.A., Thomas, R.B., Tissue, D.T. and Ball, J.T.: 1996, 'Sensitivity of leaf photosynthesis to CO_2 concentration in an invariant function for C_3 plants: a test with experimental data and global applications', *Global Biogeochem. Cycles* **10**, 209–222.

Matthews, R.W., Nabuurs, G.J., Alexeyev, V., Birdsey, R.A., Fischlin, A., Maclaren, G. and Price, D.T.: 1996, 'WG3 summary: Evaluating the role of forest management and forest products in the C budget', in M.J. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global C Cycle*, NATO ASI Series 1: Global Environmental Change, Springer-Verlag, Heidelberg, **40**, 293–301.

Morrison, I.K., Winston, D.A. and Foster, N.W.: 1976, *Urea Dosage Trial in Semi-mature Jack Pine Forest, Chaplean, Ontario: Fifth Year Results*, Can. For. Serv., Inf. Rep. O-X-251.

Natural Resources Canada: 1997, *Canada's Energy Outlook 1996–2020*, Energy Forecasting Division, Energy Policy Branch, Energy Sector, Natural Resources Canada.

Nagle, G.S.: 1990, *Trees for Canada Program*, Forestry Canada.

Nabuurs, G.J.: 1996, 'Significance of wood products in forest sector carbon balance', in M.J. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global C Cycle*, NATO ASI Series 1: Global Environmental Change, Springer-Verlag, Heidelberg, **40**, 245–256.

Nyboer, J. and Bailie, A.: 1997, *Analysis of the 1995 Industrial Energy Use Data in Canad*a, Canadian Industrial energy End-use Database and Analysis Centre, Simon Fraser University, Canada.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S.: 1987, 'Analysis of factors controlling soil organic matter levels in Great plains grasslands', *Soil Sci. Soc. Am. J.* **51**, 1173–1179.

Price, D.T. and Apps, M.J.: 1996, 'The global C cycle, forest products and forest biomass', in M.J. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global C Cycle*, NATO ASI Series 1: Global Environmental Change, Springer-Verlag, Heidelberg, **40**, 211–216.

Ro, C., Vet, R., Ord, D. and Holloway, A.: 1995, *Canadian Air And Precipitation Monitoring Network (CAPMoN) Annual Summary Reports (1983–1994)*, Atmos. Environ. Serv., Environment Canada.

Santer, B.D., Wigley, T.M.L., Barnett, T.P. and Anyamba, E.: 1996, 'Detection of climate change and attribution of clauses', in J.T. Houghton et al. (eds.), *Climate Change 1995: The Science of Climate Change*, Cambridge, Cambridge University Press, pp. 406–443.

Schimel, D.S., Braswell, B.H., Mckeown, R., Ojima, D.S., Parton, W.J. and Pulliam, W.: 1996b, 'Climate and nitrogen controls on the geography and timescales of terrestrial biogeochemical cycling', *Global Biogeochem. Cycles* **10**, 677–692.

Schlamadinger, B. and Marland, G.: 1996, 'C implications of forest management strategies', in M.J. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global C Cycle*, NATO ASI Series 1: Global Environmental Change, Springer-Verlag, Heidelberg, **40**, 217–229.

Siltanen, R.M., Apps, M.J., Zoltai, S.C., Mair, R.M. and Strong, W.L.: 1997, *A Soil Profile and Organic C Data Base for Canadian Forest and Tundra Mineral Soils*, Ottawa, ON, Canadian Forest Service.

Smith, W.N., Rochette, P., Monreal, C., Desjardins, R.L., Pattey, E. and Jaques, A.: 1997, 'The rate of carbon change in agricultural soils in Canada at the landscape level', *Can. J. Soil Sci.* **77**, 219–229.

Tarnocai, C.: 1997, 'The amount of organic C in various soil orders and ecological provinces in Canada', in R. Lal, J.M. Kimbel, R.F. Follett and B.A. Stewart (eds.), *Soil Processes and the C Cycle*, Boca Raton, CRC Press, pp. 81–92.

Volney, W.J.A.: 1996, 'Climate change and management of insect defoliators in boreal forest ecosystems', in M.J. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global C Cycle*, NATO ASI Series 1: Global Environmental Change, Springer-Verlag, Heidelberg, **40**, 79–88.

Weetman, G.F., Krause, H.H., Koller, E. and Veilleux, J.M.: 1987, *Interprovincial Forest Fertilization Program 1968–1983*: *Results of Ten-Year Growth Remeasurements*, Can. For. Serv., Inf. Rep. DPC-X-21.

Weetman, G.F., Dallaire, L.C. and Fourier, R.: 1995, 'Long-term effects of repeated N fertilization and straw applications in a jack pine forest. 1. Twenty-two-year growth response', *Can. J. For. Res*. **25**, 1978–1983.