SPECIAL PAPER

original - **MS14**

Forests, the global carbon cycle and climate change

M.J. Apps

Natural Resources Canada, Canadian Forest Service, Pacific Forestry Center,
506 West Burnside Road, Victoria, BC, V8Z 1M5, Canada. Tel: 250-363-0625.
mapps@nrcan.gc.ca

Introduction

Earth's climate has changed during the past century and will continue to change significantly over the next few centuries. Despite relatively modest changes of + 0.6 ± 0.2 °C in global mean temperature so far, ecological impacts and disruptions to human infrastructure are already evident. The predicted changes for the next 50 to 100 years are larger and faster than previously thought (Intergovernmental Panel on Climate Change [IPCC], 1990; 2001). They are also more certain. Without purposeful mitigation, changes in global mean temperature over the next 100 years will be at the high end of, or even exceed the IPCC 2001 predictions of + 1.4 to 5.8 °C above the temperatures of the 1990s (Reilly *et al*., 2001) – itself a decade of record-breaking temperature (World Meteorological Organization [WMO], 2002).

Change has not been, and will not be, evenly distributed over the planet. Climate changes are greatest at mid- to high latitudes and over continental land masses, where large populations dwell and rely on ecosystem services for their sustenance. Nor are the changes expected to be simple linear increases in temperature or other climatic variables: abrupt and inherently unpredictable changes (surprises) similar to those seen in the geological record must be expected in the future. The impacts that have already been recorded over the twentieth century will likely intensify over the twenty-first, profoundly affecting natural ecosystems and the services that society has come to depend on.

Climate change is arguably the most important environmental issue of the twenty-first century. It will have significant implications for resource management strategies. Are forests and forestry part of the problem or part of the solution (Apps and Kurz, 1991)? This paper examines the contribution of forest ecosystems and their management to the global carbon cycle.

Climate change and the global carbon cycle

In 2001 the IPCC concluded that most of the warming observed over the last half of the twentieth century can be attributed to human activities that have increased greenhouse gas concentrations in the atmosphere. They also warned that these changes will continue to drive rapid climate changes for several centuries to come (IPCC, 2001). Chief amongst these greenhouse gases is CO_2, whose atmospheric concentrations have been dramatically altered by human perturbations to the global carbon cycle.

Over at least the 420 000 years prior to the twentieth century, the atmospheric concentration of CO_2 only varied between ~ 80 ppmv (parts per million volume) (during the glaciations when the global temperature was 8 – 9 °C colder than today) and ~ 180 ppmv (during the interglacial periods where the temperature was similar to present values). This range of variation in atmospheric CO_2 is remarkably narrow, given that its concentration is determined by a highly dynamic biogeochemical cycle.This suggests that the global carbon cycle was controlled by powerful biological feedback processes to maintain a close balance between net photosynthetic uptake of CO_2 by the biosphere and its total respiration—the net source and sink strengths of the biosphere was very close to zero over at least the last 420,000 years.

There is convincing evidence that the biosphere has played a major role in regulating Earth's climate. In particular, recent data shows that although there have been periods during which Earth's temperature changed abruptly without discernable accompanying changes in the atmospheric CO2 concentrations, the converse does not appear in the glacial-interglacial records (Smith et al. 1999). The warming from glacial to interglacial conditions was relatively rapid, while the cooling phase leading to glaciation was initially rapid (possibly suggesting perturbation by an external event), but eventually gradual (indicating strong feedbacks that act to counter the change). These patterns suggest a long-term asymmetry in the global rates of CO2 uptake and release by the biosphere (Falkowski et al. 2000). The terrestrial and ocean ecosystems act as buffers to maintain the global temperature in a habitable range. In contrast to the long-term record, the atmospheric CO_2 concentration today is ~ 370 ppmv – nearly

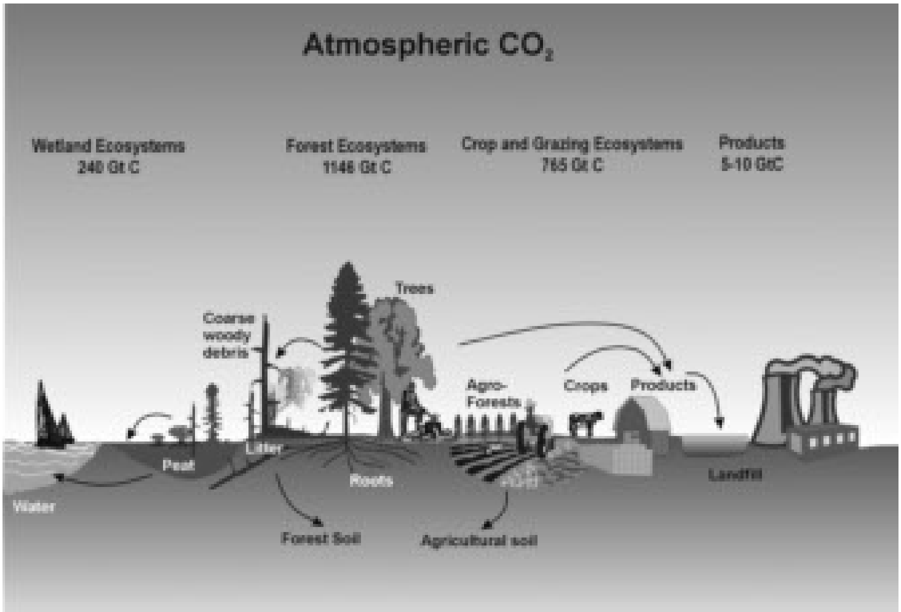

Figure 1 The natural terrestrial carbon cycle

35% higher than at any time in the past 420 000 years – as a result of human perturbations to the global carbon cycle. The concentration is also rising at a rate that is at least ten times and perhaps as much as one hundred times faster than ever before observed (Falkowski *et al*., 2000). Clearly the biosphere's regulation of the global carbon cycle – and hence the climate system – has changed. Although it is straightforward to quantify the direct anthropogenic inputs of CO_2 to the atmosphere, a quantitative explanation of the rates of atmospheric increase has proven immensely challenging, precisely because of the strong feedbacks exerted by terrestrial and ocean ecosystems to the changes. Understanding of the biospheric feedback – the response of the world's biota to the perturbations – is needed both to gauge the magnitude of future impacts and to design appropriate mitigation actions.

Human perturbations to the global carbon cycle

Human perturbations to the carbon cycle have been both direct and indirect. Obvious direct effects are the addition of new carbon to the active[1] global carbon cycle through the combustion of fossil fuels, and the modification of the vegetation structure and distribution through land-use change. Deforestation, the removal of forest vegetation and replacement by other surface cover, has the largest land-use change impact on the carbon cycle, both through the loss of photosynthetic capacity in forest vegetation and the simultaneous release of large carbon stocks accumulated in forest ecosystems over long periods of time. Indirect human impacts on the carbon cycle include changes in other major global biogeochemical cycles, alteration of the atmospheric composition through the additions of pollutants as well as CO_2, and changes in the biodiversity of landscapes and species.

Currently about three-quarters of the direct human perturbations to the global carbon cycle are due to fossil-fuel combustion, emissions of which currently exceed 6 Gt C/yr (gigatonnes of carbon per year) and are still increasing. To provide perspective, this emission is equivalent to the total incineration of half of all the trees in Canada – with no residues, charcoal or soot. Every year. Since the mid-nineteenth century, however, the cumulative addition of anthropogenic CO_2 to the atmosphere by land-use change has been nearly as large (~ 156 Gt C) as that from fossil fuel use (~ 280 Gt C), and continues to be an important anthropogenic emission (2.2 Gt C/yr) (Houghton, 2003).

Of the 7.6 ± 0.8 Gt C/yr of CO_2 added to the atmosphere by human activities during the period 1980 to 1995, only 3.2 ± 1.0 Gt C/yr remains there, with the rest taken up about equally by the oceans and by terrestrial ecosystems (Houghton, 2000)[2]. Earth's biosphere thus actively removes some of the new carbon that humans have added. Terrestrial ecosystems, in particular, sequestered (took up and retained) 2.3 ± 0.9 Gt C/yr, even after accounting for the loss of 2.0 – 2.2 Gt C/yr from deforestation (Houghton, 2003).

---

[1] "Active" is used here to distinguish the carbon pools and processes that dominate the exchange that occurs on time scales of the order of years to decades, from those that are important on geological time scales, such as the accumulation of organic carbon in fossil fuel reserves.

[2] The error estimates (±) given are the standard deviations of annual variability, not the overall uncertainty (Houghton, 2003).

Of pressing importance in the search for mitigation strategies – activities that slow or reverse the buildup of atmospheric CO_2 – is the understanding of the mechanisms responsible for the present net biospheric uptake. Will these mechanisms continue to offset direct anthropogenic emissions? Or will they decline in strength, or even fail entirely as the carbon cycle-climate system moves into a new mode of operation (Falkowski et al., 2000), as several new terrestrial and ocean model simulations alarmingly suggest (Betts *et al.*, 1997; Sarmiento *et al.*, 1998; Cox *et al.*, 2000)? Answers to these questions are of obvious importance to human society.

The anatomy of sources and sinks at the stand and landscape scale

A forest ecosystem acts as a "sink" (a net removal of atmospheric CO_2) when there is an increase in the sum of all carbon stocks retained in the forest vegetation itself and the derived stocks of organic carbon in other reservoirs. The most important of these derived reservoirs are the detritus and soil organic matter pools of the forest ecosystem.

Figure 3 shows the conceptual pools and transfers of carbon involved in forest ecosystems and in the forest sector. In addition to the ecosystem compartments (vegetation, detritus and soil pools) and the exported pools that are located off-site (including forest products and the waste created during their manufacture and abandonment in landfills), the use of fossil-fuel reserves by the forest sector is also shown.

The net carbon balance in a forest ecosystem (NEP) can be estimated by summing all the changes in ecosystem carbon stocks (the 'inventory' method), or by direct measurement of the net exchange of CO_2 with the atmosphere (e.g. eddy correlation techniques). Provided all stocks and fluxes are accounted for,

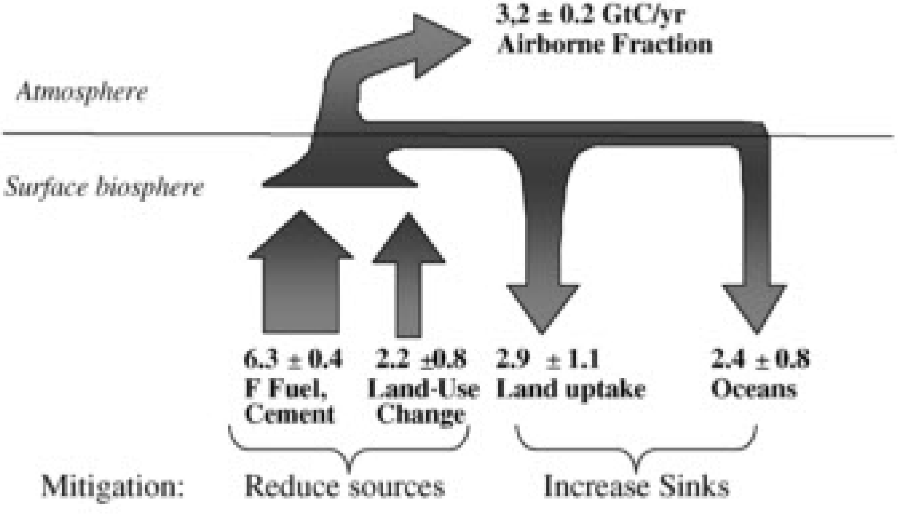

Figure 2 Human perturbations (Gt C yr^{-1}) to the global carbon cycle during the 1990s. Land uptake is inferred as residual of other fluxes and observed increase in atmosphere. Data from Houghton 2002.

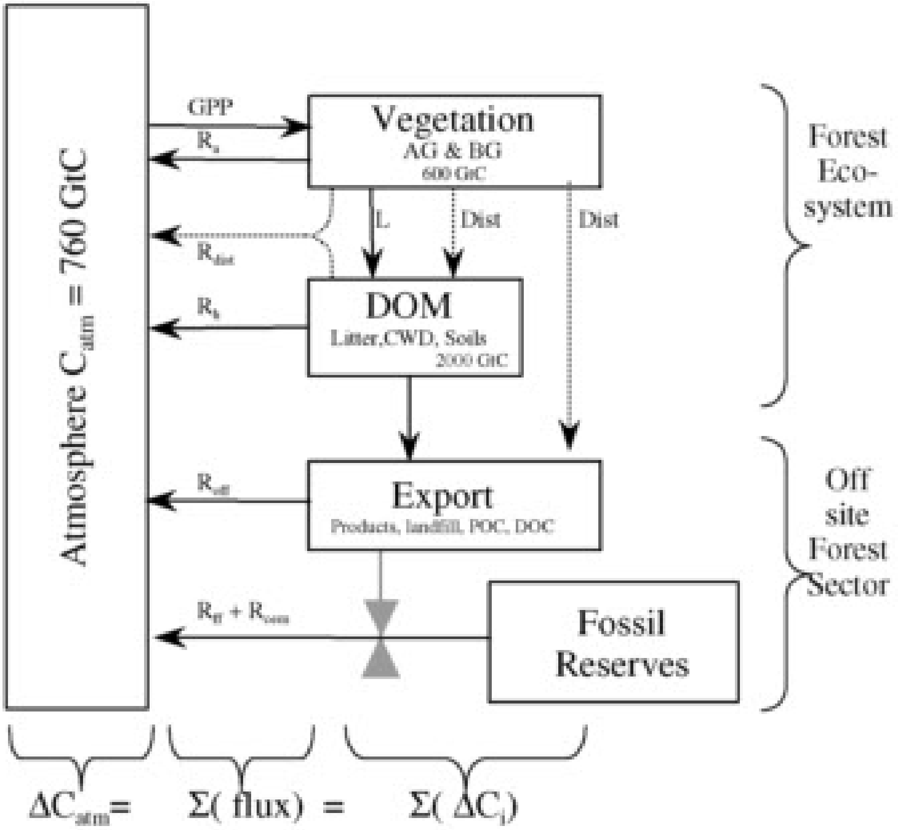

Figure 3 Carbon fluxes (arrows) and pools (boxes) involved in the forest sector budget. Smoothly varying fluxes include GPP = gross primary production, Ra = autotrophic respiration, Rh = heterotrophic respiration, Roff = offsite respiration, L= litter fall (Ag and Bg) and leaching from DOM (dead organic matter on the forest floor and in soils. Pulsed fluxes (dotted lines) are associated with disturbances. Fluxes from offsite carbon pools (products, landfills, POC=particulate organic carbon, DOC=dissolved organic carbon in water or air) are lumped into one flux Roff. The influence of bioenergy and use of forest products on fossil fuel use is shown as a control valve.

the two approaches must give identical answers (conservation of mass). In practice, a combination of the two approaches is used.

The net carbon balance of a given stand of trees (patch) varies with the prevailing conditions (affecting rates of CO_2 uptake and release) but also depends strongly on the stage of development of the stand and its past history. At the landscape (or biome) scale, a forest is a mosaic of many stands of trees (individual ecosystems) in various stages of development. The net carbon balance at this scale is the summation across all such ecosystems in the landscape.

Change in the net carbon accumulation at the landscape scale thus has two components: changes in the productivity of the individual ecosystems with environmental variations and the changes in the age-class distribution associated with landscape variation in mortality and recruitment. The age-class distribution is a histogram of the fraction of the forest in each age class (typically 10 or 20 years), and is a record of past mortality and recruitment events.

Landscape sources and sinks of atmospheric carbon can arise from changes in ecosystem productivity or from changes in the disturbance regime. If the disturbance rates increase, the age-class distribution shifts to the left (younger stands) and the total carbon retained in the ecosystems in the landscape decreases – the landscape is a transient net source of CO_2 to the atmosphere until a new stable age-class distribution is reached. (If carbon is transported out of the ecosystem landscape to decompose in off-site reservoirs, such as forest products, the landscape source is reduced by that amount – in essence this component of the source is exported.) Similarly, if disturbances are suppressed, the distributions shift to the right (older forest stands) and carbon stocks increase with a transient net removal of CO_2 from the atmosphere.

The existing land-based carbon sink and its likely future

Until recently, the net land-based carbon sink required to balance the perturbed global carbon budget (Figure 2), was explained primarily by enhanced forest uptake rates – increased GPP – associated with elevated atmospheric CO_2, increased nutrient inputs from pollution, and a positive response to global temperature increases. Changes in land-use practices, however, are now known to be responsible for some of the present land-based sink.

While physiological mechanisms driven by variations in climate can explain some of the short-term changes (seasonal to interannual) in forest ecosystem C uptake (GPP), the trends in longer-term net uptake and retention (GPP-R) are less certain (Canadell *et al*., 2000, Steffen and Tyson 2001). The distribution of the carbon taken up within forest ecosystems, and the respiration from these enhanced carbon stocks, may also increase in response to the same environmental stimuli. In addition, each of the stimulation mechanisms has limiting factors that eventually lead to a decrease in its importance over time (Canadell et al. 2000). Finally there is a concern that changes in the disturbance regime (rate, intensity and form) will increase substantially with climate change. The impact of changes in disturbance regime over the last few decades in Canada's forests has been shown to be responsible for a shift of these forests from a significant sink to a small source of atmospheric CO_2 (Kurz and Apps, 1999).

Mitigation opportunities

Land management, especially forestry and forest management, can contribute to mitigation aims both by maintaining healthy ecosystems and thereby helping to maintain, if not increase the natural land-based carbon sink, and by reducing anthropogenic emissions of CO_2 from these forests (Figure 2). These two opportunities are not mutually exclusive, and will be briefly described in very broad terms.

Forest management to increase or maintain terrestrial ecosystem carbon

The various forest ecosystem management activities that have been proposed (Binkley *et al*., 1998; Kauppi *et al*., 2001) can be grouped into three broad approaches: strategies that seek to maintain and preserve existing forests; those that aim to increase the area of land under forest; and those that attempt to increase the carbon stock density on the forested land (C/ha).

Managing services derived from forests for carbon benefits

Products extracted from managed forest ecosystems play multiple roles in the global carbon cycle: they act as an off-site, manageable carbon reservoir; they can be burned to provide a renewable source of energy; and they substitute for competing materials having a larger atmospheric CO_2 footprint.

Forest products as a manageable carbon pool

The trade of forest products results in a spatial displacement of the source component (at the site of the decomposing product) relative to a comparable sink component (in the forest ecosystem). The carbon contained in forest products makes a small, and manageable, contribution to the global carbon balance.

Globally, the net effect on atmospheric concentration is negligible unless the rate of decomposition in the geographically displaced product pools is different from that in the forest ecosystem from which it was removed. Controlling these rates through wise management, however, can offer some degree of mitigation of the increases in atmospheric CO_2.

Use of forest biomass for bioenergy

Forest-derived organic materials can also serve to reduce anthropogenic emissions in two important ways: by directly supplying energy services (bioenergy) and by supplying essential products and services that otherwise cause fossil fuel CO_2 emissions. (Figure 3 shows this emission reduction role as a control on the fossil-fuel emissions.)

The trend of increasing replacement of traditional wood-based construction products by cement, metals such as steel and aluminium, and plastics has an adverse impact on the global carbon cycle by increasing the combustion of fossil fuel for their production. For example, the CO_2 emissions associated with electrical transmission line towers is estimated at ~ 10 t C/km when manufactured from tubular steel and ~ 4.3 t C/km from concrete, in contrast to the ~ 1 t C/km estimated for roundwood poles (Richter, 1998). Similar ratios are found for other materials such as aluminum and PVC, that require expenditures of energy in their production (Richter, 1998), but which are increasingly becoming substitutes for traditional wood products.

Conclusions: The global forest sector and the global carbon cycle

Over the past 420 000 years or more, the global carbon budget has been remarkably stable, with small changes (± 20%) in the net balance, expressed by atmospheric carbon stocks, accompanying relatively small fluctuations (± 5 °C) in the global average temperature. The nineteenth century, however, witnessed the start of a dramatic change in this balance that today has already seen a 68% increase in CO_2 relative to the average of the past 420 000 years, an increase whose rate is still rising. This change has been driven by human perturbations to the global carbon cycle. These perturbations have been both direct, introducing new carbon to the active cycle through fossil-fuel use and land-use change, and indirect, affecting the biospheric part of the active carbon cycle through other environmental changes, and through perturbations to other global biogeochemical cycles. The observed response of the global climate system to this change over the last 100 years, expressed in terms of global mean temperature, is modest (+ 0.6 °C) but has already caused detectable impacts.

The predicted changes in climate over the next 100 years are more certain and predicted to be higher, and faster, than previously estimated – as much as + 6 °C or more by 2100. Although terrestrial (and ocean) ecosystems currently accommodate ~ 60% of the direct anthropogenic inputs of CO_2 to the atmosphere, the physiological mechanisms thought responsible for this increased uptake are unlikely to function as effectively in the future. Thus, in the absence of purposeful mitigation, the land-based CO_2 sink will likely decrease and could even become a source over the coming century (Cox *et al*., 2000), leading to even greater climate changes.

Sustainable development in forestry has an important role to play in reversing these trends. This role is not restricted to the maintenance or enhancement of carbon stocks in forest ecosystems but can include reduction of fossil-fuel emissions. The sustainable use of forest products – including bioenergy to displace the use of fossil fuels and avoiding the use of alternative materials with a higher energy content – may make a much more significant contribution to mitigating climate change in the longer term, because it avoids the introduction of new carbon into the active carbon cycle, while supplying essential goods and services to society.

The sustainable use of forests can provide a potential win-win situation: maintenance of carbon stocks in healthy forest ecosystems, the cost of which may be offset by the continuous stream of forest products, which themselves help to avoid the direct input of new carbon into the atmosphere. Good forestry is part of the solution.

References

Apps, M. J. & Kurz, W. A. 1991. The carbon budget of Canadian forests in a changing climate: can forestry be part of the solution? (Abstract). In *Extended Abstracts for 'ISCORD '91', 3rd International Symposium on Cold Region Development, Edmonton, June 16-20, 1991.* Alberta Res. Council.

Betts, R. A., Cox, P. M., Lee, S. E. & Woodward, F. I. 1997. Contrasting physiological and structural vegetation feedbacks in climate change simulations. *Nature* 387: 796–799.

Binkley, C. S., Apps, M. J., Dixon, R. K., Kauppi, P. & Nilsson, L.-O. 1998. Sequestering carbon in natural forests. *Crit. Rev. in Environ. Sci. and Tech.* 27: S23–45.

Bousquet, P., Peylin, P., Ciais, P., Querre, C. L., Friedlingstein, P. & Tans, P. 2000. Regional changes in carbon dioxide fluxes of land and oceans since 1980. *Science* 290: 1342–1346.

Canadell, J. G., Mooney, H. A., Baldocchi, D. D., Berry, J. A., Ehleringer, J. R., Field, C. B., Gower, S. T., Hollinger, D. Y., Hunt, J. E., Jackson, R. B., Running, S. W., Shaver, G. R., Steffen, W., Trumbore, S. E., Valentini, R.& Bond, B.Y. 2000. Carbon metabolism of the terrestrial biosphere: A multi-technique approach for improved understanding. *Ecosystems* 3: 115–130.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. & Totterdell, I. J. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 409: 184–187.

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Hogbeg, P., Linder, S., MacKenzie, A. F., Moore, B. III, Pedersen, T. F., Rosenthal, Y., Seitzinger, S., Smetacek, V. & Steffen, W. 2000. The global carbon cycle: a test of our knowledge of Earth as a system. *Science* 290: 291–296.

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J. L., Takahashi, T. & Tans, P. 1999. The North American Sink. *Science* 483: 1815a.

Hendrickson, O. Q. 1990. How does forestry infuence atmospheric carbon? *Forestry Chronicle* 66: 469-472.

Houghton, R. A. 2000. Interannual variabiity in the global carbon cycle. *J. of Geophys. Res.* 105: 20121–20130.

Houghton, R. A. 2003. *Why are estimates of the terrestrial carbon balance so different? Global Biogeochemical Cycles.* In press (accepted Jan 2003).

IPCC. 1990. *Climate change 1990: IPCC scientific assessment.* New York, Cambridge University Press.

IPCC. 2001. *Climate change 2001: The scientific basis.* Contribution of Working Group I to the Third Assessment Report of the IPCC. Cambridge, Cambridge University Press.

Kauppi, P. E., Sedjo, R. A., Apps, M. J., Cerri, C. C., Fujimori, T., Janzen, H., Krankina, O. N., Makundi, W., Marland, G., Masera, O., Nabuurs, G. J., Razali, W. & Ravindranath, N. H. 2001. Technical and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. *In* B. Metz, O. Davidson, R. Swart, & J. Pan, eds. *Climate change 2001: Mitigation.* pp. 310–343. Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge, Cambridge University Press.

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

Reilly, J., Stone, P. H., Forest, C. E., Webster, M. D., Jacoby, G. C. & Prinn, R. G. 2001. Uncertainty and climate change assessments. *Science* 293: 430-433.

Richter, K. 1998. Life cycle assessment of wood products. *In* G. Kohlmaier, K. Weber, & R. Houghton, A, eds. *Carbon dioxide mitigation in forestry and wood industry*, pp. 219-248. Berlin, Springer Verlag.

Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J. & Manabe, S. 1998. Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature* 393: 245-249.

Smith, H. J., Fischer, H., Wahlen, M., Mastroianni, D. & Deck, B. 1999. Dual modes of the carbon cycle since the last glacial maximum. *Nature* 400:248-250.

Steffen, W. & Tyson, P. 2001. *Global change and the Earth system: A planet under pressure.* Stockholm, The Global Environmental Programmes. International Geosphere-Biosphere Programme Science No.4, IGBP.

UNFCCC. 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. *In* FCCC/CP/1997/7/Add.1.(also available at http://unfccc.int/).

WMO. 2002. WMO Statement on the status of the global climate in 2001. WMO-No. 940. Geneva.