ESTIMATING CARBON BUDGETS OF CANADIAN FOREST ECOSYSTEMS USING A NATIONAL SCALE MODEL

Michael J. Apps, Werner A. Kurz, and David T. Price

ABSTRACT

Forest managers, ecosystem scientists and policymakers are becoming increasingly concerned about possible effects of predicted changes in climate on forest carbon budgets, and about how management strategies should be adapted to respond to these changes. The Canadian boreal forest and sub-arctic ecosystems are carbon repositories of global significance that may prove particularly sensitive to possible climate changes predicted for northern mid-continental areas. For these reasons, we have developed an integrated model of the processes affecting the carbon budget of Canadian forests and forest sector activities. The structure of the carbon budget model and its estimates of forest sector carbon pools and fluxes are reviewed. Effects of ecosystem disturbances (wildfire, insect attacks causing stand mortality and various harvesting methods) are simulated by the carbon budget model, allowing sensitivity of the carbon budget to changes in these disturbance regimes to be investigated. The carbon budget model was used to generate a complete carbon budget for the Canadian forest sector for a single reference year (1986), using disturbance statistics representative of the decade 1980-1989. The contribution of the Canadian boreal forest regions to the national carbon budget was found to be significant and very sensitive to realistic changes in the areas burned annually by wildfires. Further development of the carbon budget model is in progress to allow its use for analysis of possible climate change and management scenarios over periods of several decades.

INTRODUCTION

It is an unfortunate paradox that science uses reductionist techniques to define fundamental truths, whereas high-level management generally requires that these truths be molded into simplistic approximations for broad scale application. This is particularly true of the relationship between ecosystem science and forest management because the fundamental truths about ecosystem processes are at the base of a network of great complexity, while the value of the forest resource (per hectare) is often so low that generally an extensive form of management must be practised. An additional problem may be that some forest managers are aware of the inherent complexities of the ecosystems they are managing, but this complexity discourages them from attempting to incorporate current ecological process knowledge into their long-term planning.

However, it is becoming increasingly apparent that ecosystem complexities can be of great economic and political significance, so managers and policy makers are now being confronted with forest management problems that require better understanding of ecosystem responses than can be achieved through normal line management. An important example of this concerns the role of northern forests in the global carbon cycle. Recent work by Tans et al. (1990) and others (e.g., Zoltai et al., 1991; Gorham, 1991) has drawn attention to the probable significance of northern circumpolar terrestrial vegetation as a major sink for atmospheric CO_2. It now appears possible that a significant proportion of post-industrial anthropogenic CO_2

emissions to the atmosphere (Keeling et al., 1982; Gammon et al., 1985; Rotty and Marland, 1986), is sequestered in the biomass and soils of northern high-latitude ecosystems, particularly in the vast areas of the circumpolar boreal forest and sub-arctic vegetation (e.g., Bonan, 1991). Furthermore, recent studies based on the predictions of atmospheric global circulation models (AGCMs) have indicated that the increasing atmospheric CO_2 concentration will have significant impacts on global climate and that these same northern forests are likely to be subjected to biologically significant increases in mean annual temperatures within the next 50 years or so (e.g., Schlesinger and Mitchell, 1987; Houghton and Woodwell, 1989). Some terrestrial ecologists have suggested that northern forest ecosystems may be particularly sensitive to these possible changes in climate (Zoltai et al., 1991; Rizzo and Wiken, 1989; Bonan et al., 1990).

Our current knowledge of the exact nature of these possible climate changes is limited, as is our knowledge of how the forest ecosystems would be likely to respond. However, two propositions are clear: (1) northern forest ecosystems occupy such extensive areas that their possible responses to projected imminent changes in climate are of major socio-economic importance; and (2) management decisions made for these forests today could, therefore, have very important consequences even within our own lifetimes.

This paper will briefly discuss the development and structure of a large-scale carbon budget model of the Canadian forest sector (hence referred to as the CBM-CFS). This model is intended to bridge the gap between the knowledge gained by ecosystem scientists attempting to understand the processes of critical importance to the above problems and the resource managers and policy makers who need that knowledge now to make better long-term planning decisions. The approach adopted in developing the model was intended partially to locate and identify weaknesses and gaps in existing data and knowledge. Where possible, these deficiencies have been remedied using information from the relevant scientific literature or by holding workshops to incorporate current expert knowledge. In other cases, research programs to resolve particularly crucial questions have been initiated. Results obtained from running the model for a single representative year which will be presented, demonstrate the importance of the boreal and sub-arctic ecosystems as major components of the Canadian national carbon budget will be presented. Results obtained from running the model for a single representative year will be presented, which demonstrate the importance of the boreal and sub-arctic ecosystems as major components of the Canadian national carbon budget.

RATIONALE

The total carbon budget of any geographic region is dependent on the fluxes of carbon into and out of the landscape within that region. Changes in both the inventory and annual fluxes of forest carbon can result both from natural causes (e.g., disturbances due to fire, wind and insect attack and the processes of stand regeneration, growth, competition and decay) and from human actions (e.g., silviculture, logging, land-use changes and fossil fuel consumption). These processes potentially can all result in either positive or negative impacts on ecosystem productivity and atmospheric CO_2 exchange, corresponding to accumulation or depletion of the carbon inventory. In general, resource managers do not require detailed understanding of the causes of changes resulting from possible alternate management actions (or from a changing climate), but they do need a correct interpretation of the trends and relative magnitudes of ecosystem responses to those changes. A well-designed large-scale carbon budget model, built on a correct understanding of the important ecosystem processes, can therefore

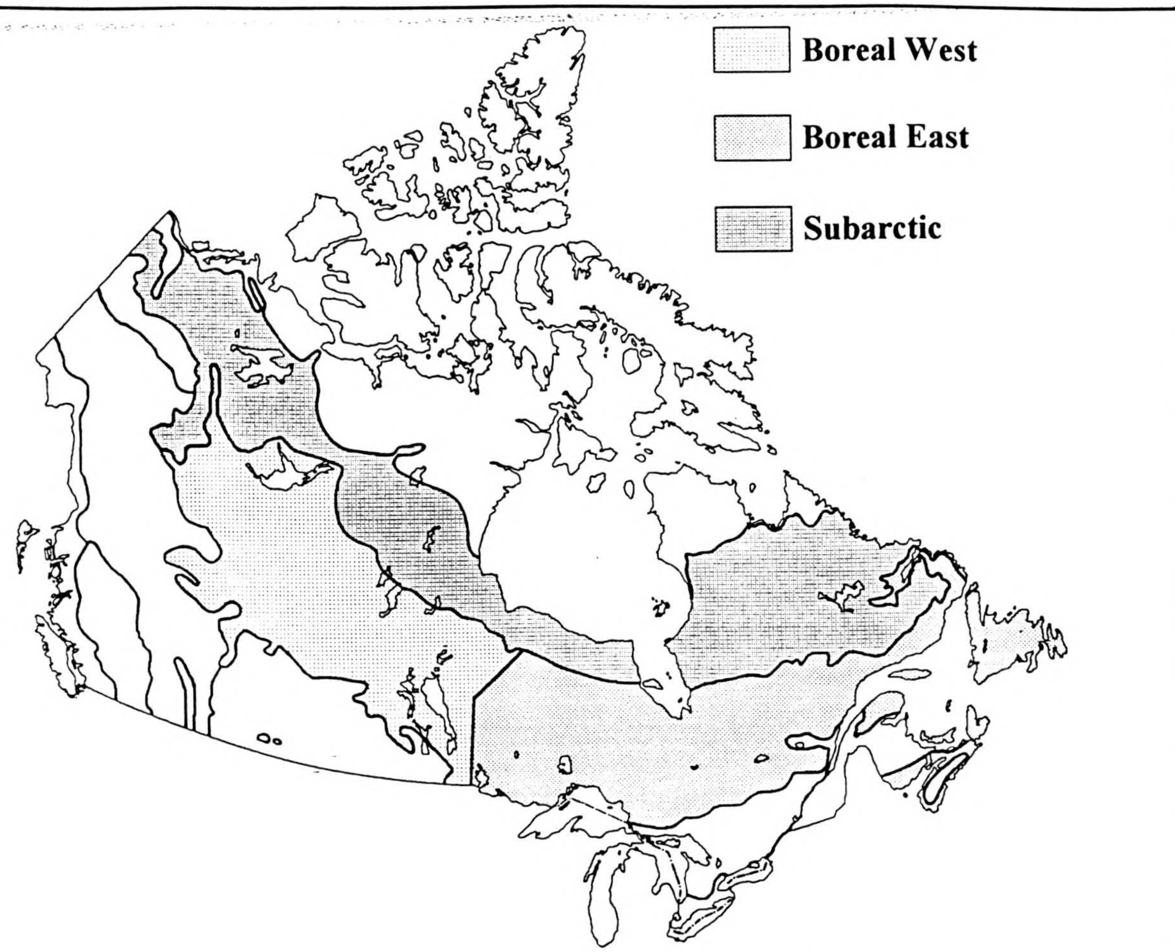

Figure 1. Outline map of the ecoclimatic provinces (EP) of Canada used in the carbon budget model of the Canadian forest sector, showing the approximate locations of the east and west boreal and sub-artic EPs (adapted from Ecoregions Working Group, 1980).

assist in deciding how the forest resource (i.e., a collection of ecosystems) should best be managed to meet particular objectives under a range of management and climate scenarios.

MODEL STRUCTURE

The development of the CBM-CFS was planned in three distinct phases. The objective of Phase 1 was to develop a model to assess the carbon budget for a single reference year, 1986, selected as representative of the current situation. Phase 2, currently under development, will allow the future effects of alternative management scenarios to be analyzed. Phase 3, when completed, will allow the national carbon budget to be analyzed as a function of management and climate change scenarios.

A detailed description of the structure of the Phase 1 CBM-CFS, and the data upon which it is based, are reported elsewhere (Kurz et al., 1991; Kurz et al., 1992), so only a brief outline will be presented here. An unusual feature of the model is that it links the carbon dynamics of ecosystem disturbances, growth and decomposition processes, forest management and the forest industry within a single integrated framework.

The CBM-CFS is based on recent forest and soils inventory data, other government and industry statistics for timber harvesting, utilization and decay of forest products and losses from fire and insect attack. From these input data, using algorithms that attempt to encapsu-

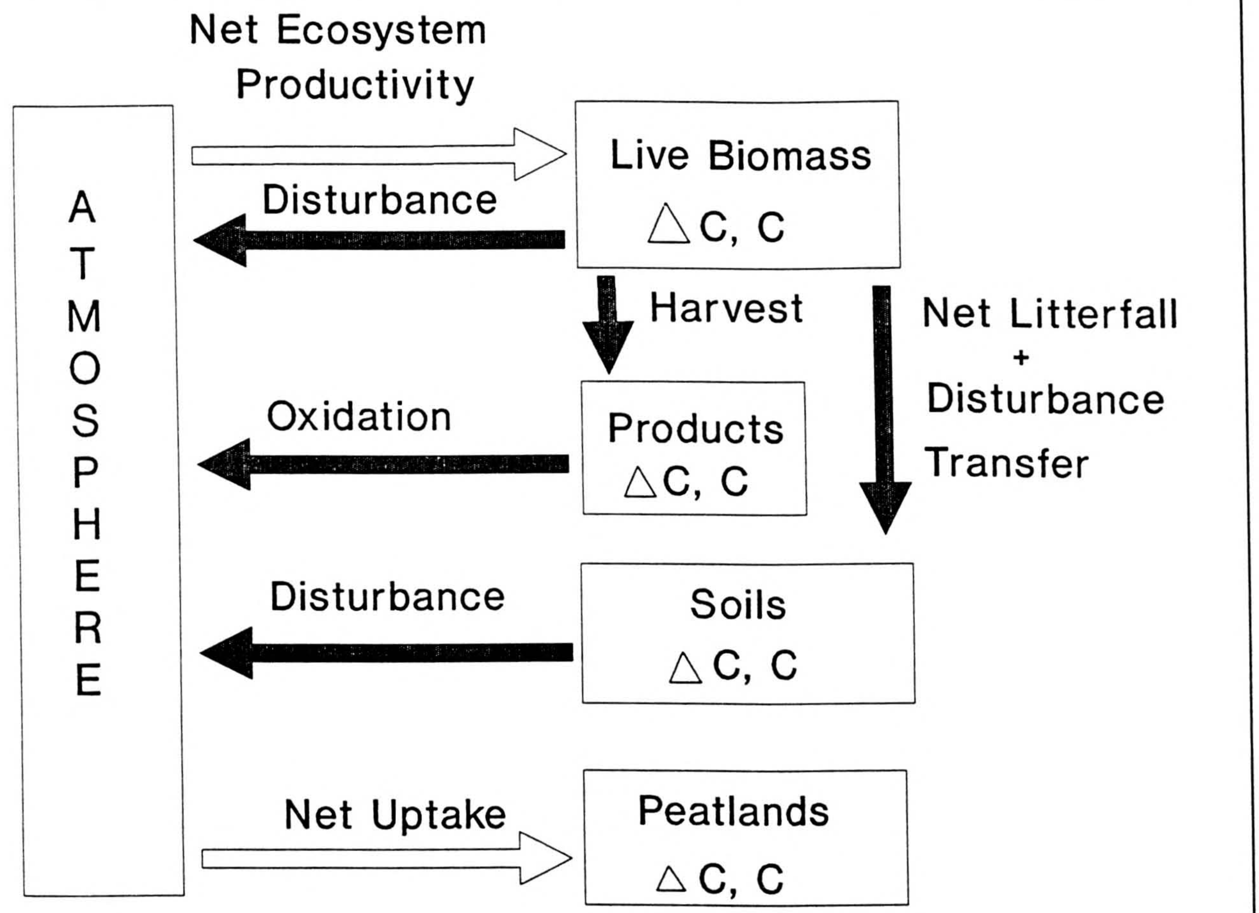

Figure 2. Relationships between carbon pools, changes in these pools and the inferred fluxes, as used in the carbon-budget model. The notation C refers to the standing stock of carbon in the pool and △C to the net annual change in that carbon pool.

late the best available knowledge of ecosystem processes, the model estimates the sizes of ecosystem carbon (C) pools and fluxes for spatial units based on the Canadian ecoclimatic classification (Ecoregions Working Group, 1989) shown in Figure 1. The estimates of the terms in the carbon budget for each spatial unit are then summed by the model to generate a national forest sector annual carbon budget. These ecoclimatic provinces have already been used for projecting future changes in vegetation cover resulting from anticipated climate changes (Rizzo and Wiken, 1989; Zoltai, 1988; Zoltai et al., 1991) Although subject to debate, these equilibrium projections indicate that the prairie grassland and cool temperate forests will migrate northwards into the areas currently occupied by boreal forest, while the current boreal forest regions will be greatly reduced. It is planned that a future version of the CBM-CFS will attempt to simulate these changes dynamically in response to the transient stages of climate change predicted to result from a doubling of atmospheric CO_2 concentration.

The CBM-CFS represents the processes affecting each of the major carbon pools found in Canadian forest ecosystems: forest biomass, soils and peatlands. In the Phase 1 CBM, only the first two pools were modeled in any detail, while peatlands were represented very simply. However, it was recognized that the boreal peatlands have historically been a very important carbon sink, and that they are potentially very sensitive to possible climate changes. In addition to ecosystem carbon pools, biomass carbon transferred to the forest product sector is tracked until released to the atmosphere.

Figure 2 shows the carbon pools and fluxes currently accounted for within the CBM-CFS, where the fluxes are inferred from estimated annual net changes in the pools. Carbon uptake is considered to occur solely through ecosystem net photosynthesis, but there are several routes by which biomass carbon may be released to the atmosphere, including decomposition of litter fall and coarse woody debris produced through harvesting, mortality and natural disturbances. Ecosystem disturbances may transfer some carbon to the atmospheric and soil pools (e.g., fire), but harvesting is distinct in that it also exports carbon to the forest products pool.

BIOMASS PRODUCTIVITY AND DECOMPOSITION

Growth curves for a range of forest types were constructed from biomass and age-class data obtained from the Canadian National Forest Biomass Inventory (Bonnor, 1985) and from Canada's Forest Inventory (Bonnor, 1982; Forestry Canada, 1988), respectively. The estimates of biomass carbon per unit land area derived from these data generally agree very well with those obtained independently by Botkin and Simpson (1990). For both the biomass and soil carbon pools, the carbon inventories were estimated by summing the area-weighted carbon mass data for each of the different forest types occurring within each spatial unit, while net carbon uptake was estimated similarly from the carbon fluxes inferred by the model.

SOIL CARBON DYNAMICS

Soil carbon and detritus are treated as three distinct pools with characteristic turnover rates: slow, medium and fast. Standing debris remaining after a disturbance, such as fire or insect attack, is added to the medium and fast turnover pools. Soil carbon data were obtained from the Oak Ridge National Laboratory data base (Zinke et al., 1986). The separate simple model for peatland areas uses historical data to estimate the annual net carbon sequestration within Canadian peatlands.

FOREST PRODUCT SECTOR

Forest sector activities affect forest ecosystem carbon dynamics, both through harvesting and through the sequestration of carbon in forest products, including disposal in landfills, while wood bioenergy is potentially important for reducing the atmospheric input of CO_2 from burning of fossil fuels. The model of forest product utilization and decay was developed using statistics going back to 1947 obtained from: provincial government records, the Pulp and Paper Research Institute of Canada, the Canadian Council of Forest Industries, private industry sources and Statistics Canada. Forest products manufactured in previous years are viewed as belonging to a series of annual cohorts. The carbon retained by each cohort is estimated from data on carbon losses due to initial processing and subsequent changes in use, including disposal and decay. The total carbon released in 1986 from decaying wood products, manufactured from Canadian forest biomass during the previous 40 years, was then estimated by summing the 1986 losses from each annual cohort. This sum was subtracted from the amount of carbon in new wood products transferred from the forest biomass pool in 1986, to give the net accumulation in the forest product carbon pool.

DISTURBANCE REGIMES

An important feature of the CBM-CFS model is that ecosystem disturbances are explicitly included so that the carbon transfers among pools resulting from disturbance events may be tracked. Canadian federal and provincial statistics were obtained for five distinct types of forest disturbance: fire, insect attack resulting in stand mortality and three types of harvesting

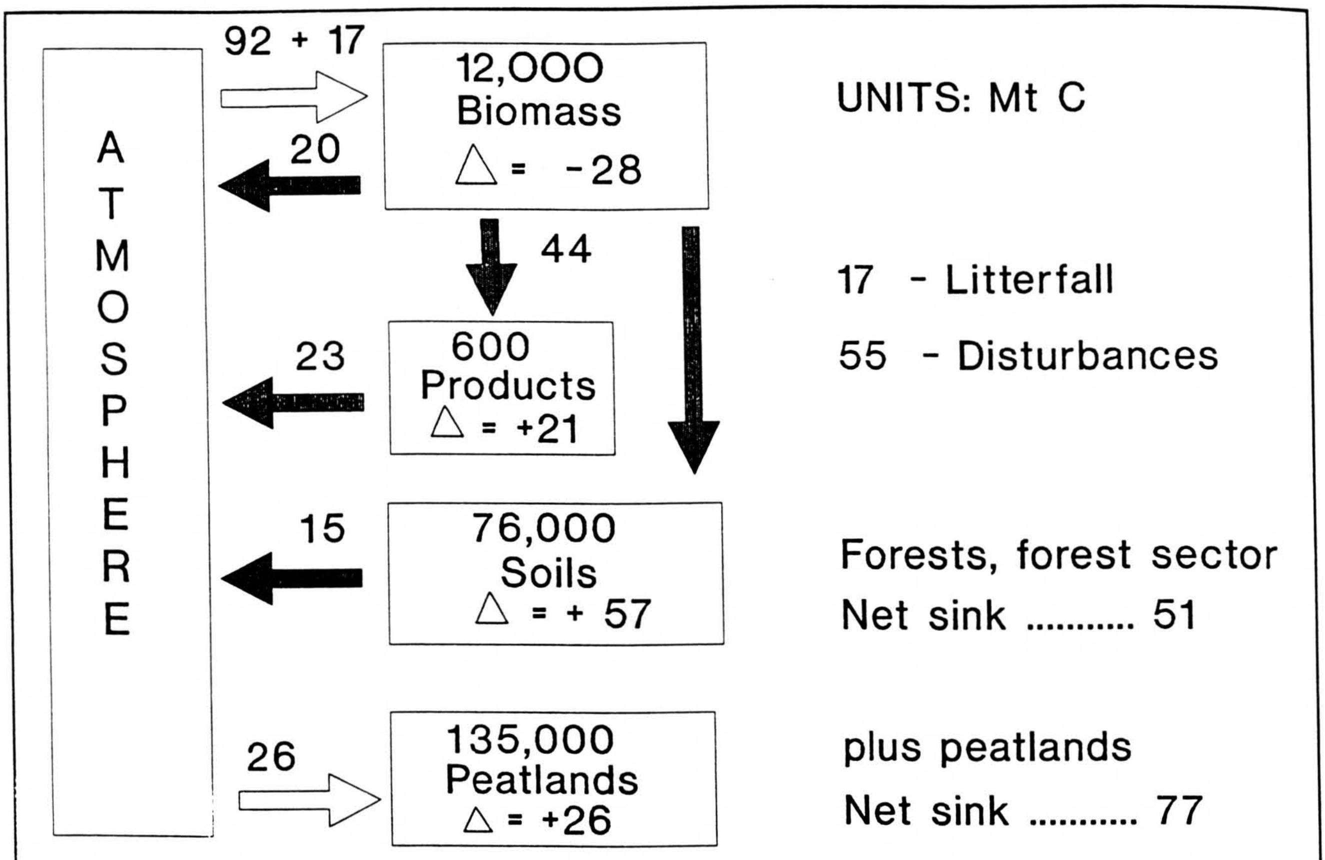

Figure 3. Summary of results obtained with the Phase I carbon budget model of the Canadian forest sector (i.e., all eleven EPs shown in Figure 1). These results refer only to the year 1986 and should not be extrapolated to other years. Units are Mt C (storage in pools) and Mt C/year (fluxes and changes in pools) (after Apps and Kurz, 1991).

regime. The total forest area annually affected within each spatial unit by each type of disturbance is allocated to stand types, based on eligibility criteria such as age and forest type (softwood, hardwood or mixed-wood).

Disturbance matrices define the proportions of ecosystem carbon transferred between individual sources (biomass and soils) and sinks (soils, atmosphere and forest products) at the time of disturbance. For example, fire generally releases only a relatively small amount of carbon to the atmosphere immediately, but transfers a larger amount into standing and fallen woody debris. Debris is treated by the model as an addition to the soil pools, and therefore decomposition over the years following disturbance is simulated by the soil submodel.

RESULTS

Phase 1: Canadian Forest Sector Carbon Budget 1986

Figure 3 shows the results obtained from the Phase 1 model, which provides a "snap-shot" of the Canadian forest sector carbon budget for the single year 1986 (Apps and Kurz, 1991). Based on these data and the carbon budget model's output, standing biomass for the national forest resource, excluding peatlands, is 12 Gt C, of which about 50% is in the Canadian boreal and sub-arctic regions. The change in that pool for the year 1986 after accounting for disturbances and removal of forest products material was a net decline of 28 Mt C in aboveground biomass (Kurz et al., 1992). However, the model estimates that disturbances transferred approximately 55 Mt C from the biomass pool to the soil pool, of which 15 Mt C were

Table 1, Carbon budget for Canadian forest biomass pools, 1986, showing impacts of carbon transfers related to disturbances. The western boreal forest is characteristically drier than the eastern boreal forest, leading to significantly greater transfers of carbon due to forest fires. Units are in Mt C/year.

	Canada	West Boreal	East Boreal	Sub-Arctic
Area (million ha)	404	98	120	85
Net Primary				
Productivity	92.0	20.0	29.0	6.6
(prior to disturbance)				
Disturbances				
Biomass -> Atmosphere				
Wildfire	18.7	11.0	2.2	2.5
Insects	0.1	0.0	0.1	0.0
Slashburning	1.5	0.0	0.1	0.0
Biomass -> Soil				
Wildfire	21.0	11.0	4.0	2.6
Insects	12.4	0.0	9.0	0.0
Logging	22.0	1.0	9.7	0.0
Biomass -> Forest Products Sector				
Logging	44.2	2.6	16.3	0.0
Net change	-27.9	-5.5	-11.7	1.4

released to the atmosphere, and the remaining 40 Mt C were added to a net gain from litter fall of approximately 17 Mt C, for a total increase in the soil pool of 57 Mt C. Meanwhile, the forest products sector, which is a relatively insignificant pool of 0.6 Gt C, gained approximately 21 Mt C through harvesting and wood processing. Peatland areas contain some 135 Gt C, and after allowing for CO_2 and methane releases, the net increase in the peatland carbon stock was about 26 Mt C (Gorham, 1991; Zoltai, 1991). Because of the carbon stored in peatland and organic soils, the boreal and sub-arctic ecosystems contain about 85% of Canadian terrestrial carbon. Canadian forest ecosystems and the forest industrial sector formed a total net carbon sink of approximately 51 Mt C, or 77 Mt C if peatland areas are included, of which the boreal and sub-arctic regions contributed about 24.5 Mt C, or 49 Mt C if peatlands are included. It is worth noting that a very different result would have been obtained if gains in forest soil carbon due to disturbances and transfers to forest products had not been considered.

Table 2. Summary of carbon budget net pool changes for Canadian forests, 1986. The forest biomass data are taken from Table 1, with corresponding totals shown for soils, peatlands and forest products. Units are in Mt C/year.

	Canada	West Boreal	East Boreal	Sub-arctic
Area (million ha)	404	98	120	85
Net Pool Changes				
Biomass	-27.9	-5.5	-11.7	1.4
Soils	57.4	7.4	23.6	1.1
Forest Products	21.1	1.2	6.8	0.0
Peatlands	26.2	11.2	8.4	5.0
Total (Net Sink)	76.8	14.3	27.1	7.5

Table 1 shows relative contributions of east and west boreal and sub-arctic regions to the Canadian national carbon budget, while Table 2 summarizes the 1986 C-budget for these areas. The boreal forest and sub-arctic regions lost 16 Mt C in biomass, but after accounting for increases in soil and peatland C stocks, they became a net sink of 49 Mt C, a very significant proportion of the national total sink for 1986. Interestingly, disturbance releases were approximately evenly distributed between eastern and western boreal forest, but in the east, they were mainly due to insect-induced stand mortality and harvesting, while in the west they were primarily due to fire. Forest products harvested from the boreal regions created an extremely large sink compared with the size of the forest product carbon pool. Hence, carbon sequestration in forest products is potentially important when assessing national forest carbon dynamics, particularly if considering future management strategies to mitigate CO_2 releases to the global atmosphere.

Sensitivity Tests - Effect of Forest Fires on the Carbon Budget

Some preliminary sensitivity tests were conducted to examine the effects of changes in disturbance regimes on the national carbon budget because these were useful both for verification of the model, and to get a first assessment of their significance under possible future management and climate change scenarios. For example, a 200% increase in the area burned annually (comparable to the exceptional 1989 fire season), resulted in a net decrease of 107 Mt C in the biomass pool and a reduction in the size of the forest sector sink from 77 to 11 Mt C. Under this extreme fire scenario, if peatland areas were excluded, the Canadian forest sector would become a net annual source of approximately 15 Mt C. It should be noted that other ecosystem changes, such as altered production and decomposition rates that might be expected in years of greater fire frequency, were not considered in this sensitivity analysis.

DISCUSSION

Phases 2 & 3: Future Improvements

One of the main purposes in initiating development of the national carbon budget model was to allow policy makers the opportunity to examine the potential effects of alternative policy decisions and climate change scenarios. To achieve this objective, several major structural enhancements to the Phase 1 model are planned or in progress. First, the Phase 2 and Phase 3 models will be able to project forward in time by simulating dynamic responses to climate change and management effects likely to influence the carbon budget during the next 50-100 years. However, the initial strategy will be to validate model predictions against responses observed during the last 40 years and attempt forward projections for a period of only 10 years. Second, for the model to respond realistically to changes in climate and management, ecosystem processes (particularly disturbance effects and physiological responses) will be simulated using a more process-based approach than currently exists in the Phase 1 model. To avoid the near-impossible task of representing ecosystem processes for all Canadian forests, parameterizations will be developed, based on the output of a planned smaller-scale (regional) version of the CBM. This will provide a linkage between small-scale processes and the total carbon budget for an individual spatial unit. The regional model is expected to operate at the level of individual landscapes (or even smaller areas such as catchments or individual stands) because many of the important ecophysiological processes are both nonlinear and highly variable even at these scales.

CONCLUSIONS

The carbon budget model of the Canadian forest sector provides a framework for estimating the terms in the Canadian national carbon budget and allows some preliminary assessment of how that budget may change in the future. On the basis of currently available forest resource statistics and assumptions derived from knowledge of ecosystem processes, the Canadian forest sector was estimated to be a net carbon sink of about 77 Mt C in 1986, of which 26 Mt C were sequestered in peatlands. The boreal and sub-arctic regions accumulated a net total of about 49 Mt C (64% of the Canadian total sink), of which about one half were due to sequestration by peatlands.

It must be emphasized very strongly that these results should not be extrapolated forward into other years because the model clearly indicates that the forest sector carbon budget is potentially very sensitive to changes both in climatic conditions and management actions. In common with other studies, the predictions obtained from the current model suffer from large uncertainties in the soils, peatlands and post-disturbance carbon dynamics. The strength of the sink appears to be very sensitive to the frequency and intensity of disturbances, as demonstrated by sensitivity tests using plausible changes in the national forest fire statistics. Therefore, it should not be assumed that the sink is sustainable under anticipated climate change with no changes in current management. Improvements to the model are planned and in process that will allow better assessment of ecosystem responses to various future scenarios of changing climate and possible alternative management strategies. These scenarios must be explored so that policy makers can be given scientifically based options, from which they should be able to make better decisions for the future management of the Canadian forest resource.

REFERENCES

Apps, M.J. and W.A. Kurz. 1991. Assessing the role of Canadian forests and forest activities in the global carbon balance. World Resource Review 3:333-344.

Bonan, G.B. 1991. Atmosphere-biosphere exchange of carbon dioxide in boreal forests. Journal of Geophysical Research 96(D4):7301-7312.

Bonan, G.B., H.H. Shugart, and D.L. Urban. 1990. The sensitivity of some high-latitude boreal forests to climatic parameters. Climatic Change 16:9-29.

Bonnor, G.M. 1982. Canada's Forest Inventory 1981. Dep. Environ. Can. For. Ser., For. Stat. Syst. Branch, Ottawa, Ontario.

Bonnor, G.M. 1985. Inventory of forest biomass in Canada. Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario.

Botkin, D.B. and L.G. Simpson. 1990. Biomass of the North American boreal forest. A step toward accurate global measures. Biogeochemistry 9:161-174.

Ecoregions Working Group. 1989. Ecoclimatic Regions of Canada, First Approximation. Ecoregions Working Group of Canada Committee on Ecological Land Classification. Ecological Land Classification Series, No. 23, Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, Environment Canada, Ottawa, Ontario.

Forestry Canada. 1988. Canada's Forest Inventory 1986. For. Can., Ottawa, Ontario.

Gammon, R.H., E.T. Sundquist, and P.J. Fraser. 1985. History of carbon dioxide in the atmosphere. In: Atmospheric Carbon Dioxide and the Global Carbon Cycle, edited by J.R. Trabalka. USDA Department of Energy, DOE/ER-0239, pp. 25-62.

Gorham, E. 1991. Northern peatlands role in the carbon cycle and probable responses to climatic warming. Ecological Applications 1(2):182-195.

Houghton, R.A. and G.M. Woodwell. 1989. Global climatic change. Scientific American 260 (4):36-44.

Keeling, C.D., R.B. Bacastow, and T.P. Whorf. 1982. Measurements of the concentration of carbon dioxide at Mauna Loa observatory, Hawaii. In: Carbon Dioxide Review: 1982, edited by W.C. Clark. Oxford University Press, New York, pp. 377-385.

Kurz, W.A., M.J. Apps, T.M. Webb, and P.J. McNamee. 1991. The contribution of biomass burning to the carbon budget of the Canadian forest sector: a conceptual model. In: Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications, edited by J.S. Levine. MIT Press, Cambridge, MA., pp. 339-344.

Kurz, W.A., M.J. Apps, T.M. Webb, and P.J. McNamee. The Carbon Budget of the Canadian Forest Sector: Phase 1. Forestry Canada Northwest Region Information Report NOR-X-326, Northern Forestry Centre, Edmonton, Alberta.

Rizzo, B. and E. Wiken. 1989. Assessing the sensitivity of Canada's ecosystems to climatic change. In: Landscape Ecological Impacts of Climate Change on Boreal/(sub) ArcticRegions with Emphasis on Fennoscandia, edited by E.A. Koster and M.M. Boer. LLIC Project, pp. 94-111.

Rotty, R.M. and G. Marland. 1986. Fossil fuel combustion: recent amounts, patterns and trends of CO_2. In: The Changing Carbon Cycle: a Global Analysis, edited by J.R. Trabalka and D.E. Reichle. Springer-Verlag, New York, pp. 474-490.

Schlesinger, M.E. and J.F.B. Mitchell. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. Reviews of Geophysics 25:760-798.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247:1431-1438.

Zinke, P.J., A.G. Strangenberger, W.M. Post, W.R. Emanuel, and J.S. Olson. 1986. Worldwide Organic Soil Carbon and Nitrogen Data. Report ORNL/CDIC-18. Carbon Dioxide Information Centre, Oak Ridge National Laboratory.

Zoltai, S.C. 1988. Ecoclimatic provinces of Canada and man-induced climatic change. Canada Committee on Ecological Land Classification, Newsletter No. 17, pp. 12-15.

Zoltai, S.C. 1991. Estimating the age of peat samples from their weight: a study from west-central Canada. The Holocene 1:68-73.

Zoltai, S.C., T. Singh, and M.J. Apps. 1991. Aspen in a changing climate. In: Aspen management for the 21st century, edited by S. Navratil and P.B. Chapman. Proceedings of a symposium held November 20-21, 1990, Edmonton, Alberta. Forestry Canada, Northwest Region, Northern Forestry Centre and Popular Council of Canada, Edmonton, Alberta, pp. 143-152.

ACKNOWLEDGEMENTS

This project was funded by the Canadian Federal Panel on Energy Research and Development (PERD) through the ENFOR (ENergy from the FORest) program of Forestry Canada. We thank the 26 experts from Forestry Canada, several U.S. and Canadian universities, and the Canadian forest industry, who freely provided ideas and data at a 3-day workshop sponsored by Forestry Canada. Joe Lowe and others from Forestry Canada's Petawawa National Forestry Institute provided national biomass data. Tim Webb and Peter McNamee have contributed significantly to the successful development of the carbon budget model. Mr. R. Mair provided valuable comments on an earlier draft of this manuscript. We also wish to acknowledge Dr. J.S. Maini, Assistant Deputy Minister, Forest Environment, whose interest has been an inspiration for this project. Mr. R. Mair provided valuable comments on an earlier draft of this manuscript.

EPA/600/R-93/084
May 1993

Proceedings
of the

International Workshop
on

CARBON CYCLING IN BOREAL FOREST AND SUB-ARCTIC ECOSYSTEMS:

Biospheric Responses and Feedbacks to Global Climate Change

Edited by

Ted S. Vinson and Tatyana P. Kolchugina

Department of Civil Engineering · Oregon State University
Corvallis, Oregon

Sponsored by

U.S. Environmental Protection Agency
Global Change Research Program
Robert K. Dixon · Program Leader
Environmental Research Laboratory
Corvallis, Oregon

September 1991

Printed on Recycled Paper