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A "MODEL FOREST MODEL": STEPS TOWARD DETAILED CARBON BUDGET ASSESSMENTS OF BOREAL FOREST ECOSYSTEMS

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ABSTRACT

The Foothills Forest, located in west central Alberta, is one of ten "model forests" established under a Canadian federal government initiative to promote sustainable development and integrated management of Canada's forest resources. The Carbon Budget Model of the Canadian Forest Sector, developed collaboratively by the Canadian Forest Service and ESSA Ltd. (Kurz, et al., 1992; Apps, et al., 1991), is being modified to allow its use of local forest inventory data, other information on local ecosystem carbon, and industrial use of fossil energy, to permit a comprehensive assessment of the current carbon budget of the Foothills Forest. The model estimates pools of carbon stored in the forest (i.e., in vegetation, soils and wetlands) and in harvested products that have left the Weldwood mills since they began operations in 1957. In addition, it examines the net annual changes in these pools due to forest growth, ecosystem disturbances, harvesting and silvicultural treatments, and decomposition (both in the forest and of forest

products in buildings and land-fills elsewhere in the world). The model also has the facility to assess biofuel consumption and to offset this against fossil fuel CO_2 emissions from forest operations. The assessment requires the compilation and analysis of all available data on forest growth and yield, ecosystem classification, soils, losses due to fires and insect attack, and historical data on harvesting and wood processing.

The anticipated end-product will be a detailed carbon budget analysis for the Foothills Forest for a single representative year (tentatively 1988), broken down by land area classifications such as ecosystem types and management working circles. The implications of prescribed scenarios for changes in management or climate (e.g., in terms of increased harvesting levels, or increased fire losses) can then be investigated, as a means of exploring possibilities for improved adaptive management for all Canadian boreal forest ecosystems.

INTRODUCTION

Canada is the custodian of 10% of the world's forested area, of which approximately 75% is classified as boreal under the current climatic conditions. These forests have become a focus of public interest in recent years, both locally and internationally. Within Canada, the environmental impacts of logging and loss of mature forest habitats are among the major perceived causes of concern; in addition, however, recent scientific developments have suggested that achieving a balance of the global carbon budget may be very dependent upon the existence of a northern terrestrial carbon sink (Tans, et al., 1990; D'Arrigo, et al., 1987). Particular attention has been focused on the circumpolar boreal forests because they are known to contain very large reservoirs of carbon (C), not merely in biomass, but to a greater extent in soils and peatlands. With global climate warming over the next 50-100 years increasingly seen as a probability, there are additional fears that the carbon contained in mid-latitude forest ecosystems will begin to be released. Carbon release will occur as wetlands dry out, soil organic matter decomposition accelerates and the occurrence of forest fires and mortality due to insects and other pests increases.

The ultimate impacts of a changing climate on these boreal ecosystems could be of considerable socioeconomic significance, and it is therefore of timely importance to investigate their current and possible future roles as sinks, or sources, of atmospheric CO_2. In fact, forest carbon budgets are beginning to be regarded as important indicators of ecosystem "health" (because net CO_2 sequestration within the system is closely related to net ecosystem productivity[1]), while there is increasing interest in the management of forests as a means of offsetting carbon emissions from fossil fuel consumption. To quantify the role of boreal forests as carbon sinks, it is important to be able to precisely assess the current carbon balance and the impacts thereon of forest management, including harvesting and wood processing.

Several large-scale forest sector carbon budget assessments have been attempted recently for northern temperate and boreal forests (e.g., Apps, et al., 1993; Apps and Kurz, 1991; Kauppi, et al., 1992; Vinson and Kolchugina, 1993; Sedjo, 1992). In general, these carbon budget assessments are based on data and algorithms which may represent a good compromise between computing limitations and data availability, but will inevitably leave some uncertainty in the final estimates. One might ask: Is it possible to determine how large this uncertainty could be? Using such models to assess the carbon budgets of smaller regions, for which detailed information is available, enables the evaluation of factors for which there are inadequate data at the national scale. Such examination can both provide a measure of confidence for the larger-scale analyses and help guide further improvements to national- and global-scale models.

A second question, strongly connected to the first, is: Can future large-scale carbon budgets be estimated successfully using process-based ecosystem level models? (Price and Apps, 1993; Price, et al., 1993). This is an important question because any attempt to use results from a number of point-based simulations derived from process-based models to provide an integrated estimate of the regional carbon budget is normally very difficult to validate. Development of a carbon budget for an entire forest unit using a modified version of the carbon budget model of the Canadian forest sector (CBM-CFS) can provide a comprehensive assessment against which scaled-up estimates derived from smaller scale models may be compared.

This paper outlines current work aimed at determining the carbon budget for the area of the Foothills Forest, a "Model Forest" located in the boreal region of western Alberta. The end-product should provide local forest managers with some of the information they will need to deal with potentially serious future economic and ecological problems. At the same time, the development of this assessment is expected to contribute to an ongoing validation of both national-scale assessments and smaller scale models while

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[1] Net ecosystem productivity (NEP) is net primary productivity (NPP) minus the releases of atmospheric carbon attributable to mortality and heterotrophic decomposition. It is therefore sensitive to changes in the processes that affect live vegetation, detritus and soil carbon pools.

providing enhanced scientific insight into the challenging problems of spatial and temporal scaling.

CARBON BUDGET MODEL

The CBM-CFS was developed collaboratively by the Canadian Forest Service and ESSA Ltd. The model's structure and operation have been extensively documented in recent papers by Apps, Kurz and coworkers (e.g., Kurz, et al., 1992; Apps and Kurz, 1991; Apps, et al., 1993). Briefly, CBM-CFS is a large-scale prognostic model that tracks the major pools and fluxes of carbon within Canadian forest ecosystems, and estimates the net carbon uptake from the global atmosphere. Using data on forest growth, soil processes, ecosystem disturbances and human activity (harvesting and wood use), the model has been used to estimate historical, current and future carbon budget assessments for Canadian forests. Each assessment is reported as an "annual balance sheet" of the carbon budget under prescribed conditions and within a specified forested region. The current model (CBM-CFS 2) assesses the national forest sector carbon budget based on 42 spatial units covering the whole of Canada (nearly 10 million km^2, of which about 4.5 million km^2 have some form of tree cover).

The objective of the present study is to modify CBM-CFS 2, and use it to derive more precise estimates of the carbon budget for smaller forest management units such as the Foothills Forest. The modified model should be generally applicable to other forested regions where suitable data are available. It will be used to calculate carbon accumulation and losses associated with locally determined rates of forest growth and decomposition, combined with local disturbance records. The assessment will include estimates of the inventory of carbon within the forest area, classified as identifiable pools including: merchantable and non-merchantable forest biomass, forest soils, and wetlands; and estimates of net annual gains and losses in these pools due to local ecosystem dynamics and management prescriptions. In addition, precise estimates will be made of the carbon exported from the forest and converted to sawn timber and other products from the forest during its operational history will be estimated, with different rates of decay applied to each group of products. The modified CBM-CFS will also be used to account for carbon released from wood-waste oxidized to generate energy, which will be segregated from carbon emissions from fossil fuels consumed in forest operations. Hence, a complete carbon budget assessment will be obtained to provide answers to key questions concerning the possible impacts of forest management, disturbances and harvesting on the forest C balance. For example: Is the forest a net sink, or source of atmospheric CO_2? and: What are the likely impacts of management and/or changes in disturbance regime (such as changes in fire frequency due to climate warming) on the net CO_2 sink/source?

THE FOOTHILLS FOREST

The Model Forest Network was initiated by the Canadian federal government as part of its "Partners in Sustainable Development of Forests" program. The stated objectives are: firstly, to accelerate the implementation of sustainable development in forestry practice, particularly the concept of integrated resource management; secondly, to develop and apply new and innovative concepts and techniques in forest management; and thirdly, to test and demonstrate the best sustainable forestry practices available (Forestry Canada, 1993). Ten Model Forests have now been established at sites representative of the five major forest ecoregions of Canada (Figure 1).

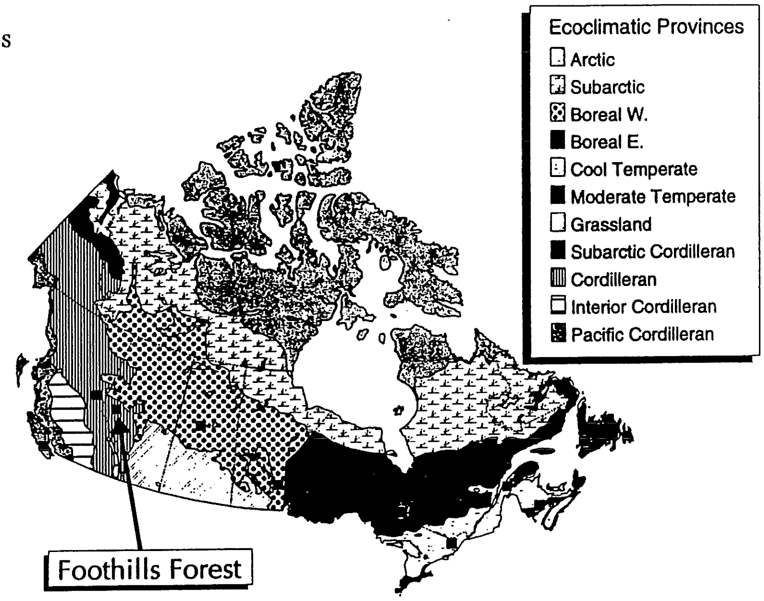

Figure 1 Map of Canada showing the Canadian ecoclimatic provinces (from Ecoregions Working Group 1989) and approximate locations of the ten Model Forest sites (from Forestry Canada 1993)

The 1.2 million ha Foothills Forest is located in western central Alberta, immediately east of Jasper National Park and the Rocky Mountains (Figure 1). It is sponsored jointly by Weldwood of Canada Ltd., which operates the forest management agreement (FMA) area and wood-processing facilities based in the town of Hinton, the Alberta provincial government, the

Alberta Forest Technology School in Hinton, and the Canadian Forest Service. In addition to these sponsors, there are over 70 partners in the Foothills Forest, including municipal and other provincial and federal government agencies, educational institutions, professional associations, unions, small businesses, consultants and environmental interest groups.

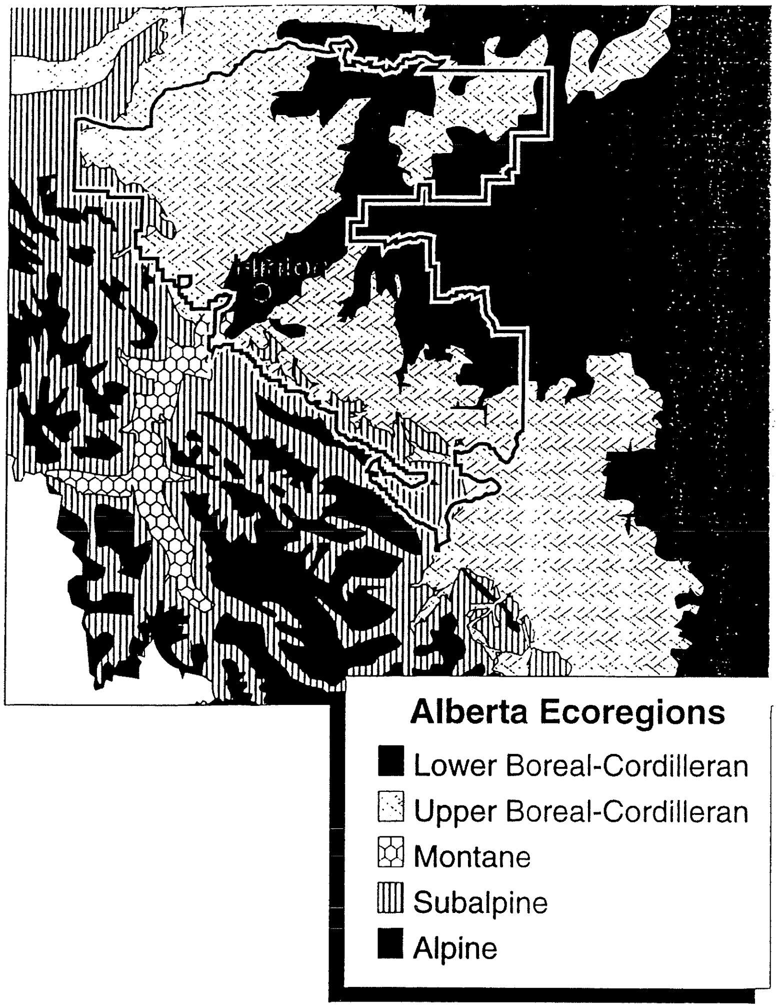

Figure 2 Map showing approximate location of the Foothills Forest boundary, superimposed on the local ecoregions (Alberta Forestry, Lands and Wildlife 1992)

The local topography features rolling hills and ridges, with an elevational gradient ranging from about 900 m at the eastern boundary of the FMA to about 1,800 m at the western edge bordering the mountains. Figure 2 shows that the Foothills Forest area lies mainly in the Upper and Lower Boreal-Cordilleran ecoregions, with small areas extending into the Subalpine and Montane ecoregions (Alberta Forestry, Lands and Wildlife, 1992). Well-drained mineral soils (gray luvisols) are most common, and the coniferous forest is composed mainly of dry-site species, lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) being predominant. This is true particularly of the Upper Boreal-Cordilleran and Montane ecoregions, though extensive areas of spruce-dominated forest are typically found in low-lying wet areas, which occur more frequently in the Lower Boreal-Cordilleran. With the exception of jack pine (*P. banksiana* Lamb.), all the tree species typically found in the western Canadian boreal forest can be found within the Foothills Forest. The Boreal-Cordilleran ecoregions are otherwise broadly similar to the southern Boreal forest ecoregions - differing only in that in the absence of fire, the natural succession usually proceeds to mixtures of white and black spruce (*Picea glauca* (Moench) Voss and *P. mariana* (Mill.) B.S.P.) with balsam fir (*Abies balsamea* (L.) Mill.) rather than to pure *P. glauca* or a *P. glauca*/*A. balsamea* mixed wood (Alberta Forestry, Lands and Wildlife, 1992). Local soils and ecosystem data have been obtained recently for the neighboring Jasper National Park by the Canadian Parks Service, and additional data will be collected from similar field studies in the Foothills Forest area.

Weldwood of Canada is the most recent of several forest management companies that have operated the FMA continuously since 1954, a period during which a high standard of forest management has been introduced and maintained. Table 1 presents a breakdown of the Foothills Forest area, within which the the FMA area is further subdivided into five working circles, each considered to be a sustained yield management unit. During the late 1950s, installation of a systematic coverage of about 3,000 permanent growth sample plots (PSPs) was initiated. Data collected from these PSPs are used to determine differences between actual and projected stand growth rates and hence update periodic estimates of the annual allowable cut (AAC). The sustained yield harvest from the entire FMA area is currently estimated to be about 2.0 million m^3 yr^{-1}, 95% of which is coniferous (Weldwood of Canada Ltd., 1992).

In addition, good data are available since operations began in 1956 of harvesting yields and the processing of harvested material through the mills. The bleached kraft pulpmill has a current capacity of 385,000 t yr^{-1} while the stud mill can process 195,000 m^3 yr^{-1}. Sawmill residues are either transferred to the pulpmill, or used as bioenergy sources. Approximately 50% of the pulpmill's chip requirements are met from the FMA, with the balance purchased from other sawmills in neighboring districts.

Table 1 Summary area break down of Foothills Forest

Weldwood FMA	
Inoperable area	210,549 ha
Operable area	801,570 ha
Total Area	1,012,119 ha
Alberta Government Management Area	205,895 ha
Foothills Forest Total Area	1,218,014 ha

The CBM-CFS allows for the possible use of forest products as energy sources, and tracks the associated releases of carbon. Currently, about 74% of Weldwood's energy supply comes from wood products (17% hog fuel and 57% black liquor) with the balance coming from natural gas (25%) and diesel fuel (1%). The Foothills Forest area contains significant reserves of coal and natural gas, many of which are currently being exploited. Releases of carbon associated with the production and utilization of these fossil fuels (other than by the forest sector itself) will not be included in the forest sector carbon budget. For ecosystem processes, only changes in organic carbon deposited within the soil profile through decomposition of plants that have established in the area since the last glaciation (more than 10,000 years ago) are considered in the CBM-CFS; over the time scales of interest (~100 years), geological formations of fossil carbon reserves are considered stable and therefore ignored.

DATA REQUIREMENTS

The carbon budget assessment requires compilation and analysis of a range of available data on forest growth and yield, ecosystem classification, soils, and historical data on disturbances (including forest harvesting and fires), as well as information on management practices. The use of Weldwood's operational records on inventories, harvesting yields, mill wood consumption and product out-turn, will provide a more accurate assessment.

In its current configuration, CBM-CFS provides carbon budget information broken down by areal groupings classified according to criteria that may be derived directly from geographic information systems (GIS). The information required for classifying forested areas includes species mix (softwood/hardwood), stocking density, site productivity, age class, land use (i.e., harvestable, or "non-productive") and stand origin (by disturbance type, if known). The Foothills Forest stand inventory data are maintained within a GIS, but some modifications or pre-processing will be required to enable CBM-CFS to operate on these data. The Foothills Forest data base provides information on the break down of the area into non-forested and forested, and the division of the latter into operable and inoperable areas. For the carbon budget assessment, precise geographic location of individual stands is not needed; consequently, all records for similar stand types can be merged to greatly reduce the data base used in the CBM-CFS calculations. There are over 300,000 records in the Foothills Forest inventory data base, which were aggregated into approximately 5,000 stand-level records to provide a stand-type classification based on criteria including primary and secondary species, canopy density, site index, year of stand origin and total area. A summary of the five-year age-class distribution of area within the FMA is shown in Figure 3.

In its current configuration, CBM-CFS provides Growth and yield data derived from the PSPs have been used to generate approximately 70 volume yield curves (YCs), which are considered to represent the entire range of growing stock conditions within the FMA. The stands identified in each inventory record can then be matched to one YC (which actually provides separate yield curves for the softwood and hardwood components), from which standing volume may be estimated as a function of age. At the Canadian national scale, however, PSPs have typically not been installed in low productivity forests of little or no commercial potential, so yield curves are not generally available for all forest types. Consequently, direct data for forest biomass growth rates were not available at a national scale, presenting a challenge for the assessment of the national forest carbon budget. To overcome this limitation, Kurz, et al. (1992) used biomass inventory data collected by Bonnor (1985) to develop approximate relationships between stand age and measured biomass (referred to as "biomass-over-age" curves) for a suite of 457 ecosystem types. These

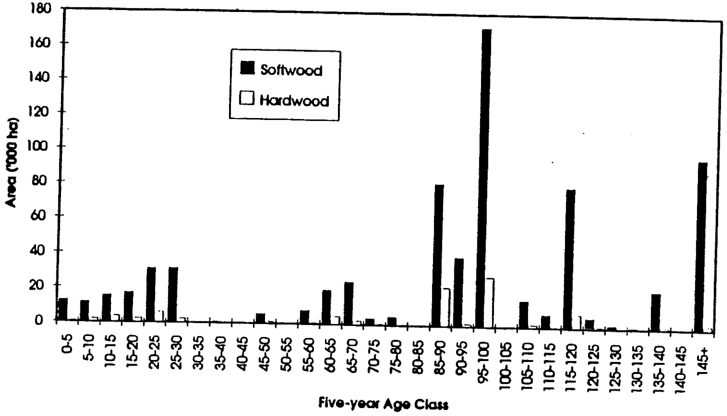

Figure 3 Age class structure of the Foothills Forest management agreement area, based on data obtained for the 1988 forest inventory (Weldwood of Canada Ltd., 1992)

curves were then used to estimate stand growth rates following annual disturbances for different ecoregions within the entire country.

The Foothills Forest study provides an opportunity to examine inaccuracies resulting from the CBM-CFS approach. Two sets of biomass-over-age curves can be derived from the stand inventory data (for ecosystems in the local boreal and cordilleran ecoregions) by using the present CBM-CFS methods and, independently, from Weldwood's PSP volume yield data. Comparison of the carbon budget estimates using these two sets of curves should be a direct indication of the inaccuracies of the CBM-CFS approach and should also indicate the sensitivity of larger-scale C budget assessments to uncertainties in these relationships.

Alternatively, because the CBM-CFS is sufficiently flexible to allow the insertion of a new biomass growth module based on Weldwood's volume yield curve calculations, the accuracy of short-term projections of biomass growth could be improved for regional estimations. Such an approach would be valid only if future environmental conditions are assumed similar to those under which the PSP data were obtained and would generally require modification in a changing climate. Whether the CBM-CFS inventory or the volume YC approach is used, merchantable timber volumes can be conveniently converted to estimates of total above-ground biomass, e.g., using species-specific empirical equations such as those derived by Singh (1984), while carbon content is taken to be 50% of dry mass. Estimation of the below-ground biomass component is, however, notoriously difficult. Based on the few available data, Kurz and Apps (unpublished manuscript) have established preliminary regression equations for predicting the ratios of above- to below-ground biomass for Canadian softwood and hardwood trees.

Soil survey data, including humified depths and carbon density, are also needed to assess the distribution and hence total carbon storage in the soils of the Foothills Forest, in combination with existing GIS polygons. Representative data are currently available for approximately 15 sites within or close to the Foothills Forest area. Survey data on accumulations of litter, snags and fallen trees are also required. Wetland areas will be assessed separately, but if found to be a significant component of the FMA, may require extra field data collection to determine their average net rates of carbon accumulation.

Records of past forest fires and insect attacks will be assessed to determine the average frequency of such events and their impacts on growth rates. Within the Foothills Forest, however, fires and insect outbreaks have been infrequent over the last 35 years, and their effects on timber yield projections are not considered to have been significant to date. In 1961, a fire-origin map showing the distribution and ages of forest stands was constructed, and subsequently updated in 1988. This age-structure information will enable the frequency of fires to be estimated in the forest before it was brought under management (e.g., see Van Wagner, 1978).

For the national scale C budget assessment, Kurz, et al. (1992) developed "carbon retention curves" to represent the average decay rates of different groups of forest products. These curves were then used to estimate the contributions to the contemporary forest product carbon pool of wood products manufactured within the previous 40 years. The same curves will be applied to Weldwood's products, based on the assumption that for any particular tree species, the geographic origin of forest products manufactured within Canada does not have any significant impact on their average lifespan. Historical records of annual sales, classified by product type (and tree species if available) will be needed in combination with the carbon retention curves, to estimate the total carbon currently retained in forest products extracted from the FMA in all years prior to and including the year of assessment.

For any given year, the difference between the inventoried timber volume on a harvesting site and the volume of timber extracted to road-side, can be used to estimate the annual transfers of biomass carbon to the forest soil carbon pool due to harvesting. Similarly, the difference between the mass of timber extracted and the sum of the masses of sawn timber and pulp and paper products sold by the mills can be used to estimate the quantity of wood waste produced during processing. The ultimate fate of this wood waste will be tracked in order to determine possible further additions to the soil, dumping in land-fills, direct releases to the atmosphere, fluid effluent discharges and substitution for fossil energy.

Data on annual fossil fuel consumption by the forest industry is needed, because the CO_2 released can be balanced against the net uptake of carbon by the forested area. Classification by operation (e.g., harvesting, transport to mill, milling, silviculture, administration) is not strictly necessary for the C budget assessment but could be of managerial importance if carbon emission controls were to be implemented. Information on electricity consumption (and its fossil fuel equivalence) would also be useful, though in the case of Weldwood's operation this appears to be an insignificant energy source, compared to consumption of organic fuels and bioenergy. Given that some wood chips processed by the pulpmill are imported from other mills not supplied by the FMA, it will be necessary to make appropriate reductions when estimating the energy consumed, and waste material produced, in processing them.

END PRODUCTS

The model will be used initially to generate a detailed carbon budget analysis of the Foothills Forest area for a single representative year (probably 1988, the date of the most recent forest inventory). The output will be presented as a balance sheet detailing carbon storage and fluxes among the identifiable carbon pools, including the current rates of atmospheric carbon uptake in forest growth, releases due to decomposition, and transfers from vegetation to soils and wood products due to harvesting and other ecosystem disturbances. The budget will be presented for the entire forest area and broken down on the basis of land area classifications including the local ecoregions and management working circles.

The sensitivity of the Foothills Forest carbon budget to prescribed disturbance scenarios will also be investigated by comparing the results with those obtained for the 1988 reference year (e.g., effects of increases in the areas annually harvested, burned or subjected to insect attack). These sensitivity tests will provide indications of the likely responses of the Foothills Forest annual carbon balance to possible future changes in climate and/or management regime. The model will then be used to generate retrospective time series data (e.g., carbon budget assessments at five year intervals under known past conditions of climate, disturbances and management), as a means of validating the model against the observed record of forest carbon dynamics. Finally, it will be used to project into the future to more fully investigate the possible long-term (50-100 years hence) responses of cumulative changes in climate and management. Specific questions to be addressed include: 1) What are the possible impacts of changes in climate (operating via effects on growth and disturbance regimes) on current net CO_2 uptake and on the sustained yield harvest, within the Foothills Forest? 2) What impact might alternative management scenarios and/or government policies have on the carbon budget of the Foothills Forest? 3) How might local management be altered to minimize climate change impacts?

DISCUSSION

It was previously stated that the Foothills Forest carbon budget study will provide an opportunity to verify regional and national scale C budget assessments made using the existing national scale CBM-CFS. In principle, the carbon pools and fluxes (expressed on a unit area basis) obtained for an entire spatial unit using regionally averaged data, can be compared with those estimated for the FMA area, using the same carbon accounting framework, but operating on the more detailed and localized data bases. In practice, however, such a comparison is not without problems.

Firstly, close agreement between these estimates is generally unlikely, because the attributes of the smaller area, such as average site productivity, can be expected to differ from the average values used for the large scale estimate. In the case of a forest management unit, this is quite probable if only because forest managers will tend to favor areas of higher than average productivity for their operations. Secondly, there is also the possibility that the conceptual framework used in the CBM-CFS is incomplete or otherwise inadequate to account for the complete carbon budget at the smaller scale of the forest management unit. The problem in this case will be in distinguishing real differences in the average C budget from those attributable to possible errors or omissions in the model framework. Running the model at the smaller scale may not expose such weaknesses directly, but it will provide a better opportunity for comparisons with independent data derived from other sources. For example, estimates of volume increment derived from regional forest inventory statistics may be compared with local estimates of increment derived from Weldwood's volume growth models applied to the forest inventory data. At a minimum, such comparisons will provide an indication of the errors inherent in the estimation of biomass carbon fluxes at the scale of the spatial unit, and provide guidance for improving the national-scale estimate.

In addition to the procedures outlined above, it will be possible to simulate forest dynamics for the Foothills Forest using a large-scale ecosystem model. Given past climate data and locally determined soil characteristics, plus information on the breakdown of site types (using digital terrain maps if possible), it is planned to run a modified version of the FORSKA 2 gap phase dynamics model (Prentice, et al., 1993) for the area of the Foothills Forest. The test will be to determine whether FORSKA 2 can successfully approximate the structure of the current forest (i.e., species composition, biomass distribution, and age-class structure). This will be an ambitious test, but a comparison between CBM-CFS and FORSKA 2 applied to the area of a 1000 km transect extending across the boreal forest regions of Saskatchewan and Manitoba, has already yielded encouraging results (Price, et al., 1993). Simulating the ecosystem processes in the area of the Foothills Forest will be considerably richer in detail, because complete detailed information on stand inventory and growth rates is available for comparison with model output. Furthermore, the significant elevational differences occurring across the area of the Foothills Forest will almost certainly require consideration of elevational impacts on climate, comparable to the latitudinal effects being investigated in the case of the boreal forest transect. If the ecosystem model can be used successfully to predict the contemporary C budget, based only on recent climate data and the local disturbance history, then an important step will have been achieved in the development of a process-based model for assessing large-scale ecosystem responses to climate.

When suitably modified, CBM-CFS can be used to calculate the carbon budget of the Foothills Forest, or of any other forest management unit for which data are available, under a range of prescribed scenarios. Responses of the forest carbon budget will be of importance in assessing possible ecological and socioeconomic consequences of changes in forest management practices, alternative harvesting methods and anticipated increases in ecosystem disturbances associated with a changing climate. Such information will clearly be of value to forest managers and policy makers alike, especially when working in the climate-sensitive boreal forest regions. As the environmental and economic concerns expressed by different interest groups become increasingly important in future forest management, the need for information to make decisions will grow significantly. The modified CBM-CFS can be used to assist long-term adaptive management (e.g., to respond to or mitigate the effects of climate change), but compiling the input data, running the model and interpreting its output requires scientific expertise.

In the longer term, it is anticipated that a suitably modified version of the CBM-CFS will be used as part of an ecologically-based decision support system (DSS). Using local forest inventory and ecological classification data maintained within a GIS, changes in the future landscape (i.e., in vegetation distribution) would be forecasted for a range of possible future scenarios using suitably calibrated forest growth models and/or ecosystem models. These forecasts would be subject to the effects of different possible management options, and their potential consequences evaluated using a suite of environmental assessment models (EAMs), of which the C budget assessment would be one (others would include habitat supply analysis, timber yield projections, and watershed and recreational impact assessments). After evaluating the output from all of the EAMs, under each of the considered options, the management strategies could be refined and the cycle repeated until an acceptable strategy emerged. This iterative process of scenario-based forecasting, evaluation and strategy refinement could be routinely updated by forest managers during management and policy decision making. If implemented for other forest management units, it would also facilitate regional- and national-scale planning, where carbon budget interests could be balanced against other resource management considerations at these larger scales.

SUMMARY

The Foothills Forest carbon budget study promises to answer some important questions about the current carbon balance of a definable area of boreal forest, and about the effects of human management activities as compared to its previous unmanaged state. With increasing concern being expressed about the possible impacts of climate change on boreal forest ecosystems, the study will also be able to assess some of the possible future impacts on net carbon uptake and projected timber yields within this area. There are at least two approaches to determining the carbon budget of the Foothills Forest: 1) downscaling the national scale carbon budget model (CBM-CFS); and 2) upscaling from canopy and ecosystem scale models. If convergence can be achieved, there will be three important conclusions. Firstly, the uncertainties in the contemporary national-scale forest sector carbon budget assessment will be better defined. Secondly, validation of process-based estimates of forest sector carbon budgets over large areas can lead the way to better projections of national scale forest responses to possible future global change. Thirdly, it will be possible to place forest-based management in context with larger-scale carbon budget assessments, i.e., to determine the relative importance of forest management actions on the national scale C budget. The last of these is particularly important because it will assist in merging economic objectives with ecological values, a primary consideration in achieving sustainable resource management, and a primary objective of the Model Forest program.

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Comprehensive assessment of carbon stocks and fluxes in a Boreal–Cordilleran forest management unit

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Abstract: A carbon budget model of the Canadian forest sector (CBM-CFS2), was modified to investigate past and possible future impacts of management on C sequestration in forest biomass, soils and harvested wood products, for a forest management unit in the western Canadian Boreal–Cordilleran ecoregions. The model showed that total suppression of natural disturbances, and their replacement by harvesting for maximum sustainable yield, could lead to significant increases in ecosystem C storage (mainly in soils and wood products) over a period of 100–200 years in this region. This is primarily because the historical interval between disturbance events (primarily wildfire) is short compared to the harvest interval. The net gains in C storage, and the period over which they are sustainable, are sensitive to several key variables, including planned harvesting levels, and the intensity of natural disturbances. A warmer climate could reduce total C storage due to greater soil decomposition, but it should not reverse the benefits attributable to management if disturbances are controlled. Extended rotation lengths increase total C storage significantly, and may justify additional investment in protection.

Introduction

The Framework Convention on Climate Change (FCCC), established at the 1992 UN Conference on Environment and Development (UNCED), led to many nations implementing policies to stabilize or reduce their greenhouse gas (GHG) emissions. While long-term stabilization can only be attained through considerable reductions in the consumption of fossil fuels, it is also clear that major reductions cannot be achieved immediately (Woodwell and Ramakrishna 1996). Conservation of global forests was also an issue on the UNCED agenda in part because the world's forests are widely perceived to act as major sinks for atmospheric carbon (C).

Within Canada, Alberta has the largest exploitable reserves of coal, oil and natural gas, which have made energy production the major industry in that Province. Alberta's forests are viewed as a potential means of sequestering a mass of C equivalent to some of the emissions, at least for the short term (next 50 years). Before an assessment of this potential can be obtained, a detailed understanding is required of the C stocks and flows in existing forests, and of the likely impacts of management practices. Only then can the real effects of any forestry project to enhance C sequestration be properly evaluated (e.g., see Matthews et al. 1996).

Alberta's commercial forests are presently managed with a sustained yield objective, although there is now increasing emphasis on ecological sustainability as a management criterion; i.e., forest values besides wood production, should also be maintainable indefinitely (e.g., Riley 1995). Sustainable management may require numerous adjustments to be made, among economic, ecological and other criteria, but sustainable timber yield will continue to be an important operational objective in the foreseeable future.

Expected impacts of sustained yield management on C storage in forests depend on management and environmental factors. Some researchers have suggested that a managed secondary forest will store significantly less total C than the primary forest it replaces, because the natural disturbance cycle governing the average age of the old growth is typically much longer than the rotation age needed for maximum volume production or profitability. Harmon et al. (1990) showed this for coastal forests of the Pacific Northwest, which exhibit natural life-spans of 200 years or more, but which have been replaced by forests managed on a 70–80 year rotation. Similar conclusions were reached for high productivity forest plantations by Vitousek (1991) and Maclaren (1996).

For Alberta forests, on the other hand, Price et al. (1996) suggested that management of lower productivity forests for timber can lead to increases in total C storage (ecosystem plus wood products) in systems where the natural disturbance cycle is shorter than the rotation age needed for maximum sustainable timber yield (MSY). If protection of the forest against fire and other losses can be maintained, so that natural disturbances are largely replaced by harvesting, then C may accumulate, particularly in soils and wood products. This paper improves on the latter study by using a more comprehensive data base and including sensitivity analysis of the model's output. The objective is to assess the likely impacts of management practices on C stocks and flows in boreal forest ecosystems, as compared to similar but unmanaged forests.

The managed forest scenarios account for the effects on C dynamics of the annual conversion of harvested trees into wood products, and of their subsequent life-cycle as they are gradually consumed, burned or allowed to decay in landfills. Specifically, two questions are addressed. Firstly, how do forest protection, silvicultural treatments and operational harvesting affect C sequestration in a managed forest? Secondly, what are the sensitivities of these effects to variation in the natural disturbance cycle and to changes in harvesting intensity?

Site description

The Foothills Forest is located near Hinton (53.5°N, 117.5°W) in west central Alberta, extending over approximately 1.2 Mha, mainly in the Upper and Lower Boreal–Cordilleran, but including small proportions in the Subalpine and Montane ecoregions (Alberta Forestry, Lands and Wildlife 1992). Lodgepole pine (*Pinus contorta* Dougl.) is the dominant species in stands covering 65% of the land area. White and black spruces (*Picea glauca* (Moench) Voss.), and *P. mariana* (Mill.) B.S.P.), are dominant in a further 20%, while aspen (*Populus tremuloides* Michx.) is dominant in mixed-woods covering much of the remaining area. The annual average temperature in this region, estimated from 1961–1990 normals for local climate stations (AES 1983), is 2.4 °C. Average soil C density for the Cordilleran ecoregion is estimated to be 84.3 Mg C ha^{-1}, derived from the Canadian Forest Service soil C data base (Siltanen et al. *in press*).

The Foothills forest management agreement (FMA) area, currently licensed to Weldwood of Canada, has been managed for large-scale timber production since 1956, although pest control and suppression of wildfires have been practised since 1915 (Weldwood 1992; Van Wagner 1978). Weldwood currently manages an area of approximately 1 000 000 ha, divided into five working circles, and extending across the four ecoregions, for which a detailed computer-based stand inventory has been compiled. Silvicultural practices include: tending of white spruce stands following release from aspen overstorey; selective logging on sensitive sites; scarification to promote natural seeding or to favour artificial regeneration; brush and weed control; and precommercial thinning of juvenile lodgepole pine stands (Weldwood 1992). Some 3000 permanent growth sample plots (PSPs), established since the mid-1950s, provide comprehensive data for the local yield models used to project annual harvest volumes. Most harvested conifer timber is supplied to company mills located in the FMA area, which produce kraft pulp and construction lumber.

Application of C budget model to the Foothills Forest

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), has been described extensively elsewhere (e.g., Kurz et al. 1992; Kurz and Apps 1994). Briefly, it estimates the C stocks contained in, and C flows among, forest biomass, soils and products using data derived from forest inventories, ecosystem classifications, soil surveys and other government and industry statistics. Annual forest growth and soil decomposition for representative stand-types are simulated using empirical relation-ships. The effects of disturbances (principally wild-fires, insect attacks and harvesting) on forest age structure and on C releases to the atmosphere and forest floor are calculated on a five-year cycle. The model has generally been used to estimate forest sector C budgets for Canada as a whole, although some studies have focused on specific ecoregions (e.g., Apps et al. 1993; Kurz and Apps 1993, 1996). The study reported here uses an object-oriented version of CBM-CFS2 applied at a higher spatial resolution than in earlier studies.

While CBM-CFS2 allows explicit simulation of the influence of climate, this study focused on management implications for carbon storage. Climatic variation amongst the ecoregions was not directly considered, although the influence of climate on biomass growth, soil pool initialization, and observed disturbance regimes are implicit in the model parameterization for each ecoregion. Uniform annual temperature and precipitation were assumed for the entire FMA in the absence of spatially explicit data.

Biomass carbon pool

Growth measurements obtained from the PSPs have been used by Weldwood to derive approximately 70 volume yield curves (YCs), considered to represent the range of growing stock conditions within the Foothills FMA area (Weldwood 1992). Each stand recorded in the forest inventory is matched to a single YC, which provides estimates of merchantable timber volume (m^3 ha^{-1}) in 10-year increments ranging from 10 to 150 years, for both softwood and hardwood components. Price et al. (1996) transformed the volume-over-age data for each YC into an equivalent dry biomass-over-age data set, estimated using Singh's (1984) merchantable volume-to-biomass conversion equations for individual species in central Canada. For YCs where maximum biomass was reached later than age 100 (typically conifers), the mature phase (where biomass is maintained constant) was considered to last from age 150 to 200. For stands reaching maximum volume before age 100 (typically aspen), the mature phase was considered to last until age 160. Following the mature phase, stand break-up was represented by a negative exponential with decay rates of 0.01 yr^{-1} and 0.02 yr^{-1} for conifers and hardwoods, respectively. Natural disturbance and harvesting intervals are typically in the range 50–100 years, so an imperfect representation of stand break-up should have little impact on estimated C dynamics.

The biomass-over-age curves were then used by CBM- CFS2 to estimate forest growth (and hence C uptake) from the Weldwood stand inventory. The inventory data base (over 300 000 records) was aggregated into 14 spatial units (corresponding to the intersections of the working circles with the ecoregions), split into 10-year age-classes, and approximately 70 stand-growth types corresponding to the Weldwood YCs.

Within the Foothills Forest FMA area, fire-origin stands of lodgepole pine are commonly observed to achieve very high stem densities (sometimes exceeding 100 000 stem ha^{-1}). This causes volume growth to stagnate within a few years (Pearson et al. 1984; Keane and Weetman 1987; Tait et al. 1988). By controlling the density of stands regenerated following harvesting Weldwood expects to increase merchantable volume production by as much as 50%.. Weldwood allocates new higher productivity YCs to stands regenerated with this silvicultural treatment.

Soil carbon pool

As forest biomass grows and dies, or is destroyed by disturbances, the C it contains is transferred to the litter layer or lost to the atmosphere. Litter and coarse woody debris then decompose, releasing much C to the atmosphere and a certain fraction to the soil. Here it again undergoes decomposition, although some may persist for decades or centuries. These processes are represented within CBM-CFS2, where plant litter is transferred directly from the biomass pool to one of three soil pools, each of which has a different decay constant. During decomposition, much of the C is released to the atmosphere, while the residues are transferred to a fourth “slow decay” pool (Kurz and Apps 1994; Kurz et al. 1995a).

For the Foothills Forest, the initial C content of the slow soil C pool for each age class of each of the 70 stand-growth types was estimated assuming a natural disturbance cycle of 50 years, and the average soil C density reported earlier. The model was run until a smooth negative exponential age-class structure (Van Wagner 1978) had been obtained, at which point the different age classes each contained an adjusted soil C density and the total soil C pool had stabilized. For each stand-growth type, the simulated soil C densities were then used to initialize the corresponding age classes for the same stand types.

Harvesting

Data on current and projected annual harvesting rates, and on the wood consumed annually by company mills, were estimated from the 1991 Detailed Forest Management Plan (FMP) (Weldwood 1992). Harvesting is planned to occur at approximately 2 million m^3 yr^{-1} for the 20-year period 1988–2007, of which 1.9 million m^3 yr^{-1} are expected from coniferous stands. Certain operational constraints are specified in Weldwood’s FMP. Firstly, stands must carry a minimum of 47.5 m^3 ha^{-1} of merchantable conifer timber to be considered operable. Secondly, the annual harvest is determined by the need for a sustained wood supply of 2 million m^3 yr^{-1}; hence areas harvested and regenerated annually may vary. Thirdly, current harvesting is concentrated on stands which are overmature, with highest volume areas harvested first, but it will shift to younger stands closer to MSY rotation age as the supply of older timber is exhausted. This strategy is subject to access constraints, however, so some lower volume stands may be harvested each year. Fourthly, MSY volumes are predicated upon assumed productivity increases due to silvicultural interventions following harvest.

Of these four constraints, the first two were directly simulated by CBM-CFS2. The third was less easy. The model normally harvests the highest volume (or biomass) stands first. To approximate accessibility limitations, annual harvest from highest volume stands was arbitrarily restricted to 20% of the stand, which forced harvesting of lower volume stands. To simulate silvicultural influences, CBM-CFS2 was modified to permit reallocation of regenerated areas to the appropriate higher-productivity YCs following harvesting .

Wood processing

Harvested material is used for production of oriented strand board (OSB), construction lumber and bleached kraft pulp. Although OSB is sometimes used for shorter lived products, for simplicity it was treated as lumber in the calculations. The transfers of forest biomass C to the soil pool during harvesting, to wood products C pools, and released to the atmosphere during processing, were accounted for as described in Price et al. (1996).

Wood product decay

The forest product sector module of CBM-CFS2, uses the forest product retention coefficients developed by Kurz et al. (1992) to make annual estimates of C contained in wood products derived from the Foothills FMA area. For each year of the simulation, manufacturing transfers C from the processing stream (harvest plus recycling) to each product pool (lumber, pulp products and landfill materials) using fixed allocation fractions appropriate for Weldwood’s operation (Price et al. 1996). Product pool sizes are adjusted according to the retention coefficients, to account for products that have reached the end of their useful life. Carbon is then transferred to the atmosphere (product combustion and decomposition), returned to the processing stream (recycling) or to a new product category (landfill or bioenergy).

Model simulations

In total, seventeen 285-year C budget scenarios were compared for the FMA area using CBM-CFS2. These were designed to investigate the past and possible future C dynamics of the area, grouped into two broad categories (Table 1). The first group (A) was based on the known history of management, harvesting and natural disturbances in the FMA area in the period 1953–1988, and explored the outcomes of possible management alternatives on the C budget for the next 250 years (referred to as "managed scenarios"). The second group of simulations (B) were comparable "unmanaged scenarios", where only natural ecosystem processes were assumed to occur in the period 1953–2238. The simulations allow testing of the sensitivity of the model's output to possible errors in assumptions, as well as investigation of effects of changes in management or environmental conditions.

To reduce bias, the simulations for both managed and unmanaged scenarios were initialized with the age-class structure of the forest as it existed before significant harvesting had begun. All stands aged 35 years or less in the 1988 inventory (Fig. 1*a*), were reallocated as older stands in 1953, based on harvesting records and a study of the local fire history (D. Farr, 1996, pers. comm.) Local records indicated that no significant harvesting occurred prior to management in the mid-1950s; since then, only small areas have been affected by natural disturbances (mainly fires). For each of the five working circles, the areas of the post-1953 stands were added to those of the remaining older age classes, assuming that the latter were disturbed in proportion to the area they occupied in the forest at that time. This produced the reconstructed 1953 age-class distribution shown in Fig. 1*b*.

These reconstructed age-class data became the initial forest inventory for all model simulations. The CBM-CFS2 tracks

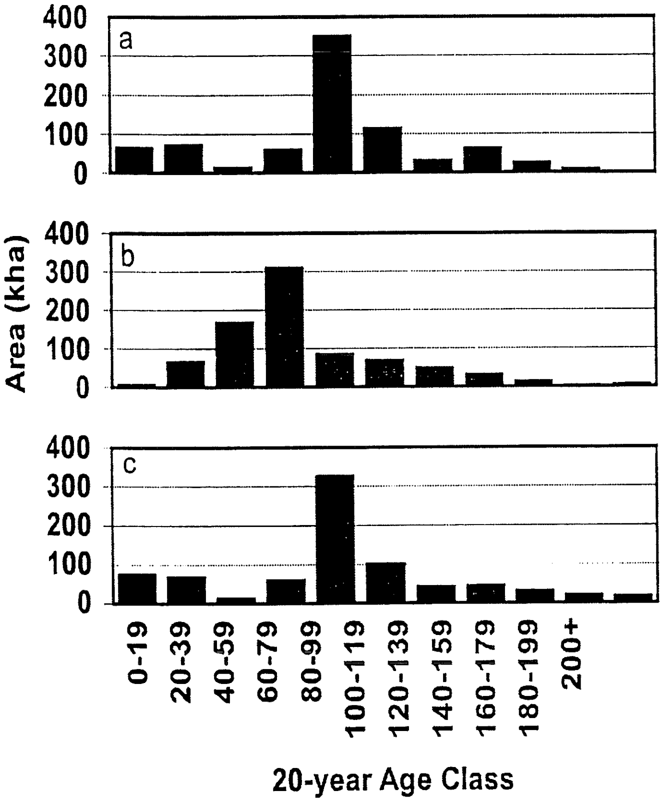
Table 1. Summary of simulations performed using the Phase 2 Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) for the Foothills Forest forest management agreement (FMA) area.

Run Description	Comments
A. Managed, no Fires, from 1953	
A0. Baseline: Harvesting at 100% of levels indicated in detailed forest management plan..	Protection from fires and insects. No productivity gains following harvesting
Sensitivity tests:	
A1. Reduce harvesting rate in 1988 by 25%	Protection from fires and insects
A2. Reduce harvesting rate in 1988 by 10%	Protection from fires and insects
A3. Increase harvesting rate in 1988 by 10%	Protection from fires and insects
A4. Increase harvesting rate in 1988 by 25%	Protection from fires and insects
A5. Increase productivity for all harvested stands.*	100% harvest + silviculture + protection from fires and insects
A6. Natural disturbances with average cycle of 50 yr starting 1953	Harvesting as recorded since 1953.
A7. Natural disturbances with average cycle of 75 yr starting 1953.	Harvesting as recorded since 1953
A8. Natural disturbances with average cycle of 100 yr starting 1953.	Harvesting as recorded since 1953; closest to observed natural disturbance cycle in 1988.†
A9. Natural disturbances with average cycle of 50 yr starting 1988	Assume no disturbances prior to 1988; harvesting as recorded.
A10. Natural disturbances with average cycle of 75 yr starting 1988.	Assume no disturbances prior to 1988; harvesting as recorded.
A11. Natural disturbances with average cycle of 100 yr starting 1988.	Assume no disturbances prior to 1988; harvesting as recorded.
B. UNMANAGED, NO HARVESTING, FROM 1953	
B0. Baseline: Natural disturbances on 50-year cycle	No management or harvesting
Sensitivity tests:	
B1. Increase natural disturbance cycle to 75 yr	No management or harvesting
B2. Increase natural disturbance cycle to 100 yr	No management or harvesting
B3. Increase soil decomposition rate by 25%	No management or harvesting
B4. Decrease soil decomposition rate by 25%	No management or harvesting
17 RUNS IN TOTAL	

* This test derives from the expectation that lodgepole pine stands regenerated following harvesting will exhibit higher volume productivity than the fire-origin stands they replace.

† There is no assurance that a 100-year disturbance cycle will represent the future regime, even assuming current protection measures are maintained.

Fig. 1. (*a*). Age-class structure of the Foothills Forest determined from 1988 forest inventory data (data from Weldwood 1992). (*b*) Approximate age-class structure of the Foothills Forest in 1953, reconstructed from 1988 data shown in (*a*), and used for C budget assessments under managed and unmanaged scenarios. (*c*) Age-class structure for 1988, simulated by CBM-CFS2 assuming known history of harvesting and disturbances since 1953, based on the reconstructed 1953 age-class structure shown in (*b*).



changes in the forest's age-class structure, so the results obtained for year 35 of the managed scenarios could be compared with the true 1988 age-class distribution. Comparison of Figs. 1*a* and 1*c* shows that fairly close agreement was obtained. The model assumes that all areas subject to natural disturbance by fire are affected with equal probability; hence, compared to reality, the reconstructed distribution tends to a smoother exponential decay curve.

In the managed scenarios, annual harvesting rates prior to 1988 were based on the areas regenerated since 1953 (known from the 1988 inventory), and for 1988 onwards, based on planned harvest volumes given in the FMP (Weldwood 1992). For the baseline simulation, scenario A0, it was assumed that natural disturbances were completely suppressed after 1953, and that there would be no changes in environmental conditions affecting growth and decomposition rates (e.g., climate change). Observed losses due to fires and insects since 1953 are small, but the effects of the assumption of complete disturbance suppression were examined by carrying out additional simulations to recreate areas disturbed during 1953–1988.

For the unmanaged scenarios, the effects of solely natural ecosystem processes on the forest sector C budget were examined over the entire 285-year period. The baseline simulation (scenario B0) assumed that the reported 50-year mean disturbance cycle (van Wagner 1978) would persist for the entire period 1953–2238, with no changes in average environmental conditions. The implications of changes in disturbance cycles are discussed later.

Sensitivity tests

Harvesting intensity

For the managed scenarios, the effects of different future harvesting rates on forest C dynamics were explored by performing four simulations (scenarios A1–A4), with the post-1988 annual harvest volume changed by ±10 and ±25%. (Harvesting in the period 1953–1988 is a matter of record.) Assumptions regarding wood utilization and the fates of wood products were unchanged from the baseline scenario (A0).

Changes in productivity following harvesting

Sensitivity test A5 assumed that increased productivity in lodgepole pine stands would occur following harvesting and that natural disturbances would be completely suppressed. These productivity increases, averaging about 50%, were applied to all areas harvested after 1953.

Natural disturbances

Van Wagner (1978) provides estimates of the mean disturbance cycle in the area of the Foothills FMA. Prior to ca. 1915, the mean disturbance cycle was approximately 50 years, but increased to approximately 65 years during the period 1915–1960, presumably in response to fire suppression practices in the area. Therefore, effects of changes in average disturbance rate were investigated, for both managed and unmanaged scenarios. In the managed scenarios, the initial assumption of complete disturbance suppression was altered to examine natural disturbance cycles of 50, 75 and 100 years. The sensitivity tests were repeated first assuming natural disturbances occurring from 1953 onwards (A6–A8) and second, assuming they began in 1988 (A9–A11). The values 50, 75 and 100 were selected assuming that the length of the disturbance cycle in managed scenarios would be equal to or greater than that used in the unmanaged baseline scenario.

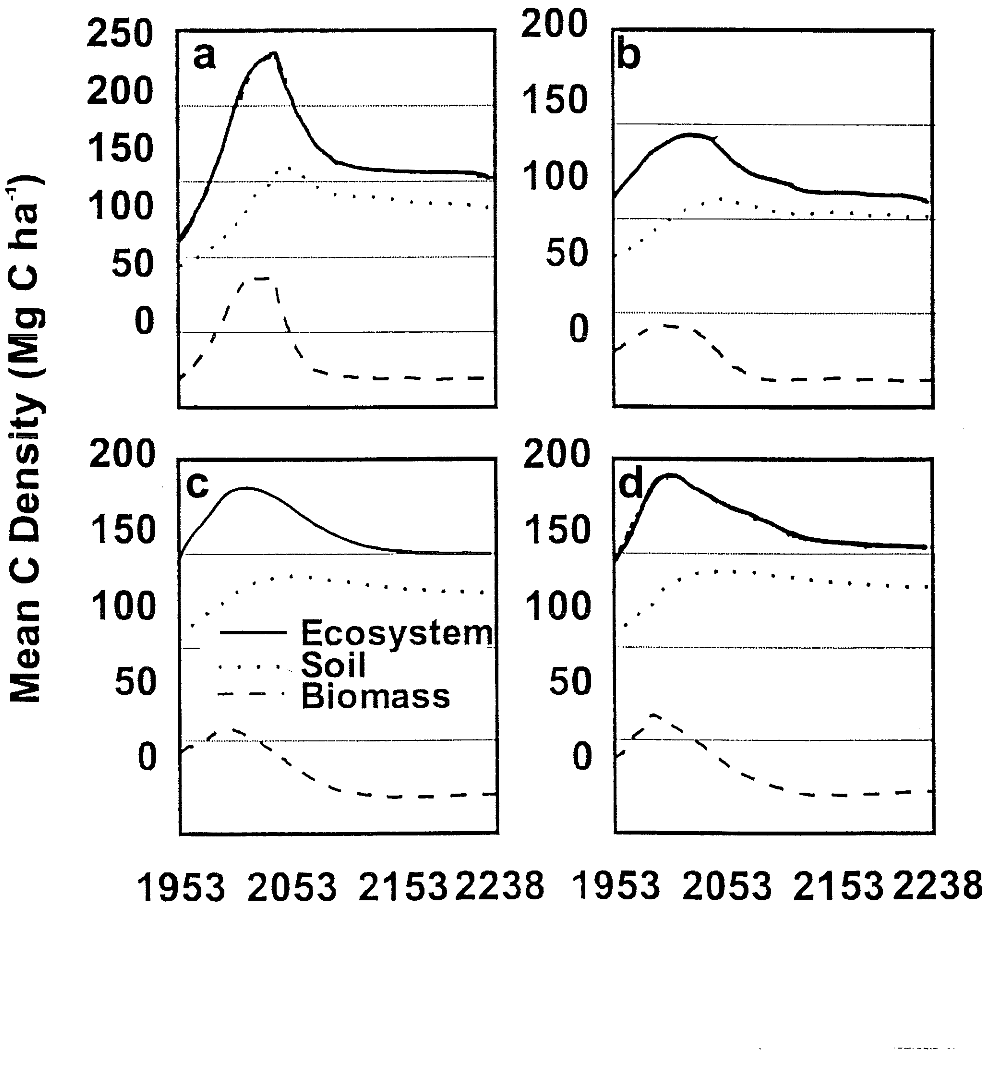
Changes in soil decomposition rate

The estimates of average soil decomposition rates used in the simulations were the least reliable model parameters. Possible effects of errors in these values were assessed by running simulations with rates changed by ±25% (B3 and B4) relative to those used in the baseline unmanaged scenario (B0).

Results

Fig. 2 shows simulated mean C storage density (Mg C ha^{-1}) in each ecoregion under scenario A0, which uses observed pre-1988 harvest data, Weldwood's post-1988 harvest projections, complete protection from fire, and no silvicultural treatments. Initially, all ecoregions show large increases in both biomass and soil C storage densities, but magnitudes and timing of maxima vary. These peaks occur because the planned harvesting program progressively removes biomass accumulated in older stands, eventually causing the standing stock to decline to the point where its annual productivity balances the annual harvest. Soil C storage density maximizes later than the biomass C density because of the transfer of litter during harvesting. Total ecosystem C densities typically peak early in the 21st century.

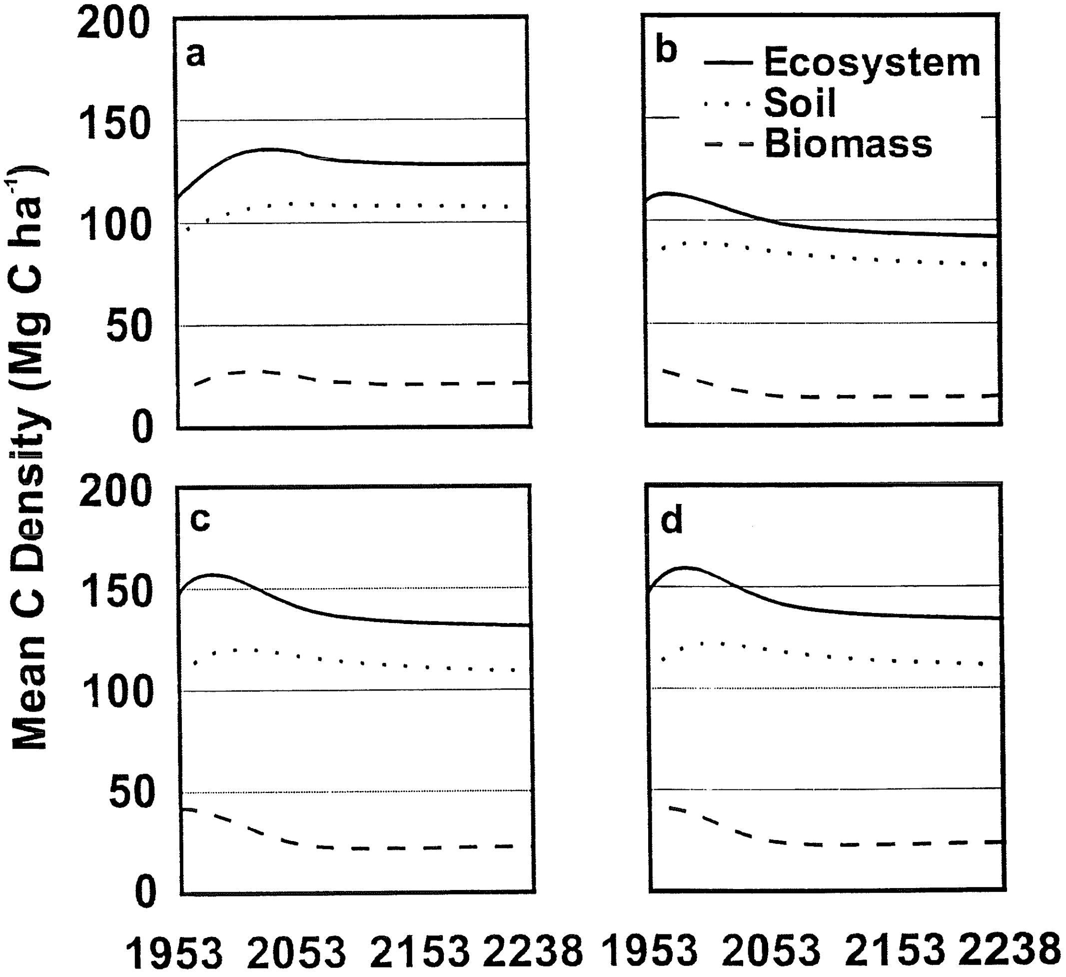
Fig. 2. Carbon budget simulation results for four ecoregions in the Foothills Model Forest forest management agreement (FMA) area, based on the reconstructed age class distribution for 1953 (Fig. 1*b*). The simulations assumed the known history of harvesting for the period 1953–1988, and planned future harvesting thereafter. Complete suppression of natural disturbances and no changes in stand productivity following harvesting were assumed for the entire simulation period. (*a*) Montane (350 ha), (*b*) Sub-alpine (105 565 ha), (*c*) Upper Boreal–Cordilleran (542 383 ha), (*d*) Lower Boreal–Cordilleran (175 359 ha). Note the smaller vertical scale for the Montane ecoregion.



By comparison, Fig. 3 gives the results of C budget simulations assuming only natural disturbances at a constant mean cycle of 50 years (scenario B0). While all ecoregions exhibit lower, and earlier peaks in soil C density, only the Montane shows a significant gain in biomass C density after 1953. This implies that the average natural disturbance cycle before 1953 was longer than 50 years in all cases (except the Montane) which may be attributed in part to the effects of fire suppression in the period 1920–1955 (see also Van Wagner 1978). These dynamics in soil and biomass density create earlier but lower peaks in total C storage, compared to the managed scenario of Fig. 2. The long-term trends lead to equilibrium in biomass C densities (which interestingly are virtually identical to those for scenario A0), but soil C continues to decline for the duration of the simulation (in all but the Montane). This can be attributed to the very long time constant assumed for decomposition in the slow soil pool, where some of the litter transferred from the biomass pool at (and prior to) the beginning of the simulated period is still being decomposed 250 years later. Hence, in all four ecoregions, total C storage density is consistently greater under scenario A0 than scenario B0.

The initial slopes of the biomass trajectories shown in Figs. 2 and 3 indicate the change in natural disturbance cycle following the start of the simulation. A negative slope (as in Figs. 3*b* and 3*c*) implies that prior to 1953, disturbances were, on average, less frequent than 50 years. Hence, the Montane ecoregion appears to be recovering from an earlier period of intense disturbance. Because it covers only 350 ha within the FMA area, this implies that a large proportion of this area burned prior to 1953. The Lower–Boreal Cordilleran appears initially to be in an equilibrium where biomass production (from stands of all ages) is balanced by losses due to disturbance. After about 50 years, however, the C losses from mature and overmature stands exceed net annual growth in younger stands, causing total biomass density to decline. This indicates that before 1953, the average disturbance cycle in this ecoregion was only slightly longer than 50 years.

Fig. 3. As Fig. 2, but assuming no management and an average 50-year natural disturbance cycle after 1953.



Results for individual ecoregions (Figs. 2 and 3) are summed (Figs. 4a and 5) to provide a direct assessment of the effects of management on total C storage (Tg C) in the operational portion of the Foothills FMA area. Additionally, Fig. 4b shows the contribution of manufactured wood products (pulp, construction lumber and material disposed in landfills). Scenario A (Fig. 4a) results in greater total C storage at all times, reaching a peak close to 160 Tg C around 2005, compared to about 125 Tg C around 1975 in scenario B0 (Fig 5). In the long-term, C storage stabilizes at about 130 Tg C under scenario A0, copared to only 105 Tg C at the end of scenario B0. As seen in Fig. 4*b*, the wood products pool varies in size, but it eventually contributes about 9% of total system C. This variation occurs because the initial high rate of harvesting results in a rapid increase in the construction lumber C pool, which then decreases while decay of finished products exceeds additions of newly manufactured material. The eventual upward trend results from the more gradual increase in the size of the landfill C pool with very slow decay.

Fig. 4. (*a*) Simulated changes in C storage in soils, biomass, wood products and total forest ecosystem for the Foothills FMA area (820 657 ha), under the managed scenario of Fig 2. (*b*) Changes in C storage in pulp products, lumber products and landfills for the wood products pool changes shown in (*a*).

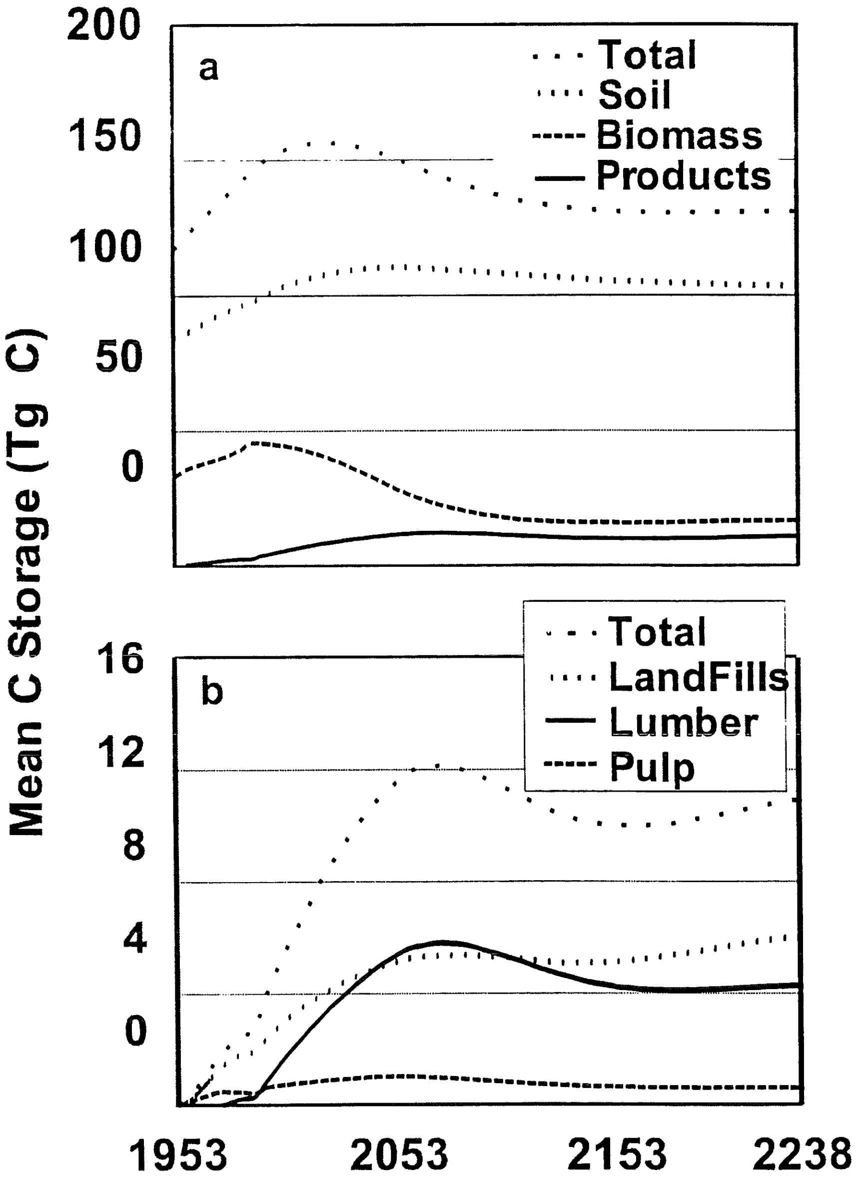


Fig. 5. As Fig. 4*a*, but for the unmanaged scenario of Fig. 3.

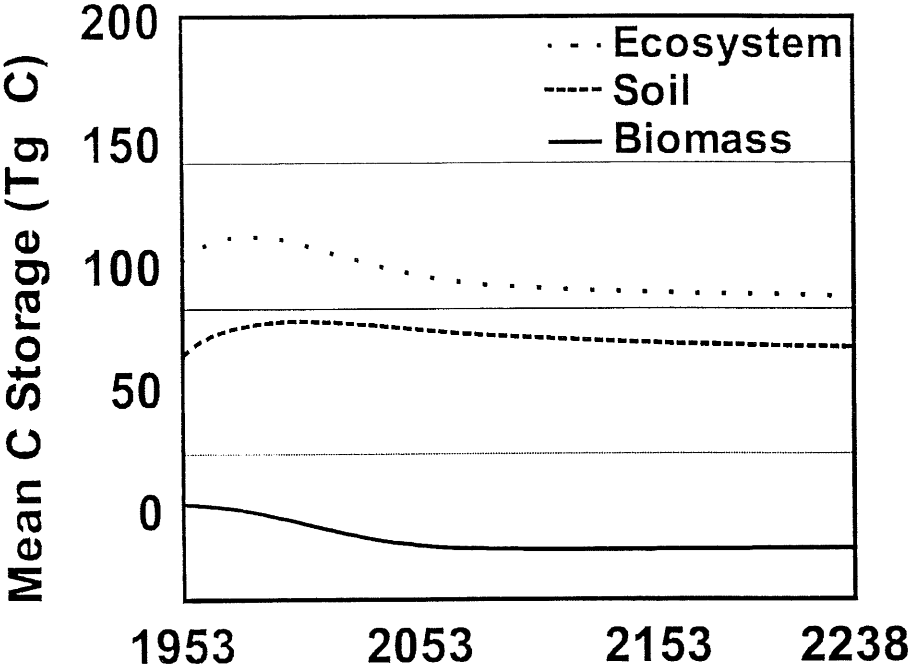


Fig. 6 shows a scenario (A7) where natural disturbances continue after 1988 with an average cycle of 75 years, in addition to planned harvesting. The initial differences in biomass C storage (cf. Fig. 4) reach approximately 5 Tg C in 1988, supporting the hypothesis that historical losses due to natural disturbances after 1953 were relatively small. For the future, however, the consequences of natural disturbances added to planned harvesting programs result in very significant reductions in total C storage, compared to those scenarios with complete disturbance suppression Natural disturbances significantly reduce timber available for harvesting, causing the contribution of products to total C to be reduced to about 5% (cf. Figs. 4*b* and 6*b*).

The additional effects of assumed gains in forest productivity resulting from post-harvest silvicultural treatments are shown in Fig. 7 (scenario A5). These results represent a best-case scenario (assuming biomass production increases in direct proportion to merchantable timber yield), which compare to the worst-case (i.e., no productivity gains) of scenario A0 (Fig. 4). Under the best-case scenario, there are no obvious gains in simulated C storage before 2025, but thereafter the declining trend in biomass C slows and eventually reverses, as old stands are gradually replaced by younger stands of higher productivity. This increased biomass production leads to a continual increase in the soil C pool, with the result that from about 2100 onwards, total C storage continues to increase for the remainder of the simulation. The productivity gains also allow planned harvesting levels to be maintained resulting in greater long-term accumulation of C in products.(Figs. 4*b* and 7*b*).

Fig. 8 compares the effects on total ecosystem storage of varying future harvesting by ±10% and ±25% of the planned level. Increased harvest levels reduce total storage, particularly in the short to medium term, but as the system tends towards a new equilibrium, i.e., as the relatively unproductive old forest is replaced by younger faster-growing stands, the overall change in total ecosystem C becomes much smaller.

Fig. 9 compares natural disturbance cycles of 50, 75 and 100 years, for both unmanaged (baseline, B1, and B2) and managed (A6–A8) scenarios. Changes in the frequency of natural disturbances have a major impact on total ecosystem C within the FMA area. Since the 1920s, the average age of the forest increased to approximately 78 yr in 1953, and to 93 yr in 1988 (estimates based on data used in Fig. 1*c*). Consequently, the projections for the 75- and 100-year disturbance cycles are likely to be closer to reality, at least for the near future, assuming no changes in current management strategy and environmental conditions. Hence, forest protection evidently contributes to appreciable increases in ecosystem C storage (see also Table 2), which largely compensate for harvest withdrawals (Fig. 8).

The level of forest protection needed to maintain total C storage at a level comparable to that of the unmanaged system, while continuing harvesting at planned levels, can be estimated from Fig. 9. Extrapolation from the trend shown by the three lower trajectories suggests that the average natural disturbance cycle would need to be 100 years or longer. If a proportion of the planned harvest could be met by salvaging timber from disturbed stands; more frequent natural disturbances could be accepted.

Fig. 6. (*a*) As Fig. 4*a*, but for a managed scenario which includes the known history of natural disturbances for the period 1953–1988, and assumes the occurrence of natural disturbances with an average cycle of 75 years for the period 1988–2238. (*b*) Changes in C storage in pulp products, lumber products and landfills for the wood products pool changes shown in (*a*).

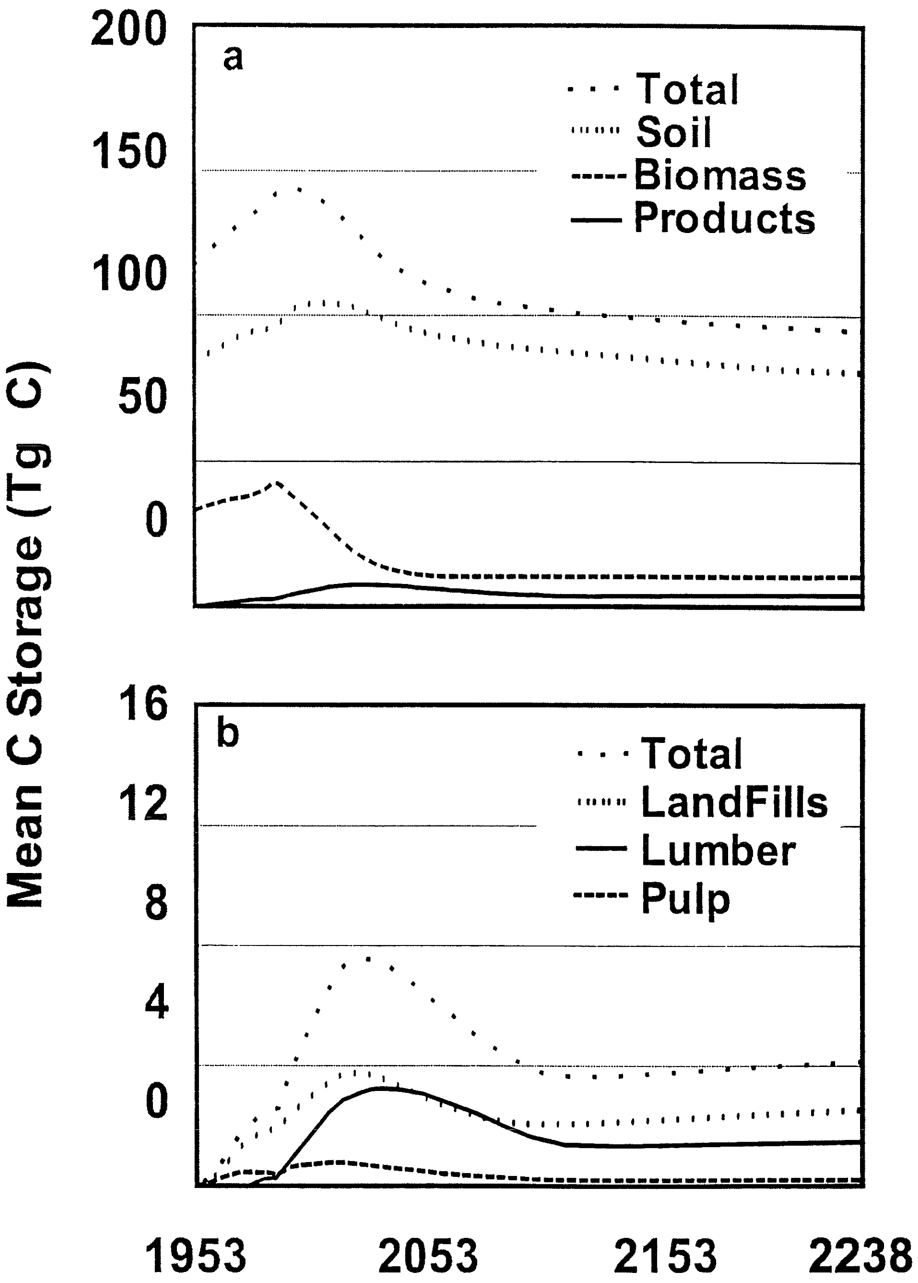


Fig. 7. (*a*). As Fig. 4*a*, but for a best-case managed scenario which accounts for productivity gains resulting from the effects of stand density control following harvesting. (*b*) Changes in C storage in pulp products, lumber products and landfills for the wood products pool changes shown in (*a*).

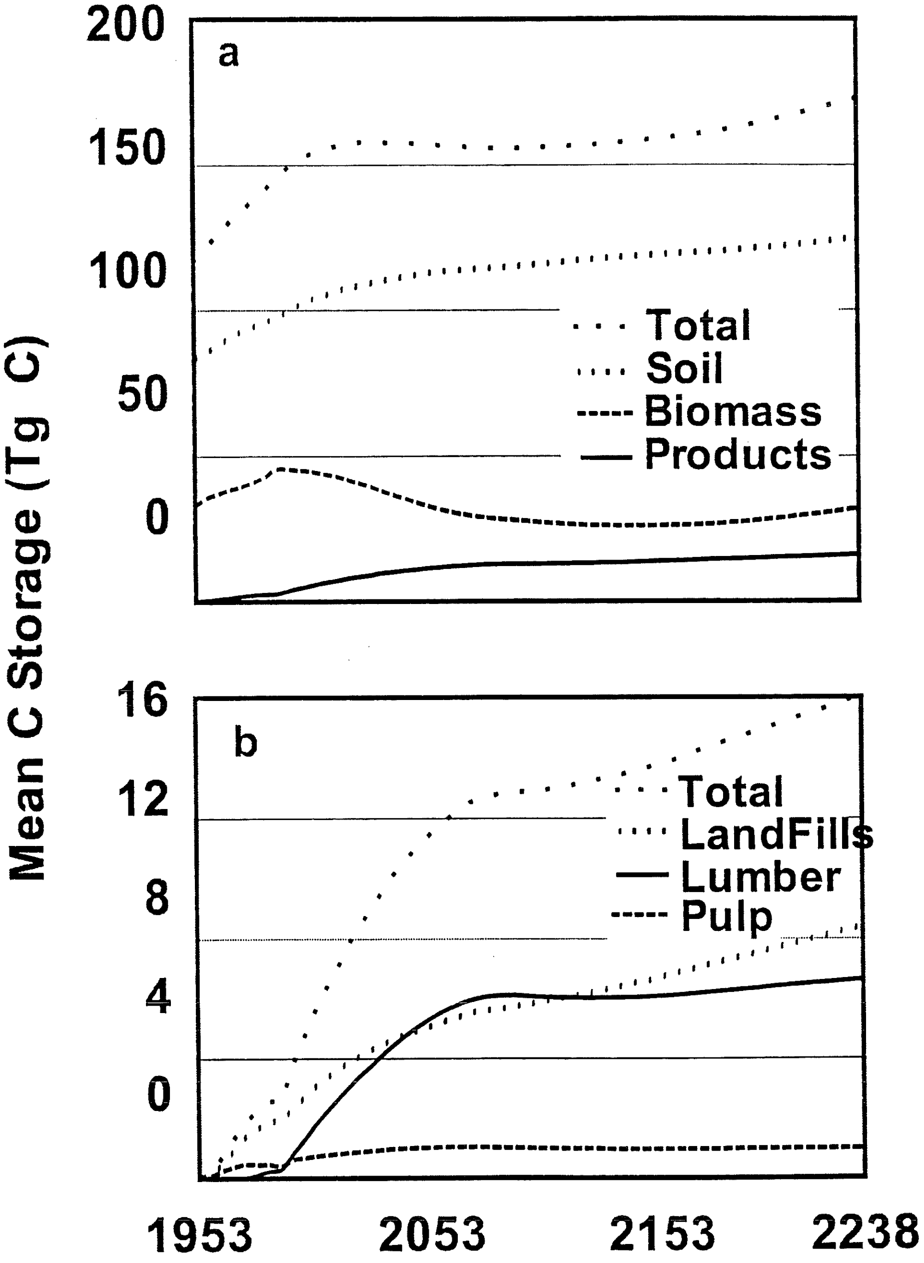


Fig. 8. Results of sensitivity tests to assess the effects of different harvesting levels (expressed as a percentage of the Forest Management Plan baseline) on total ecosystem C storage in the Foothills FMA area, simulated under the managed scenario (Fig. 4).

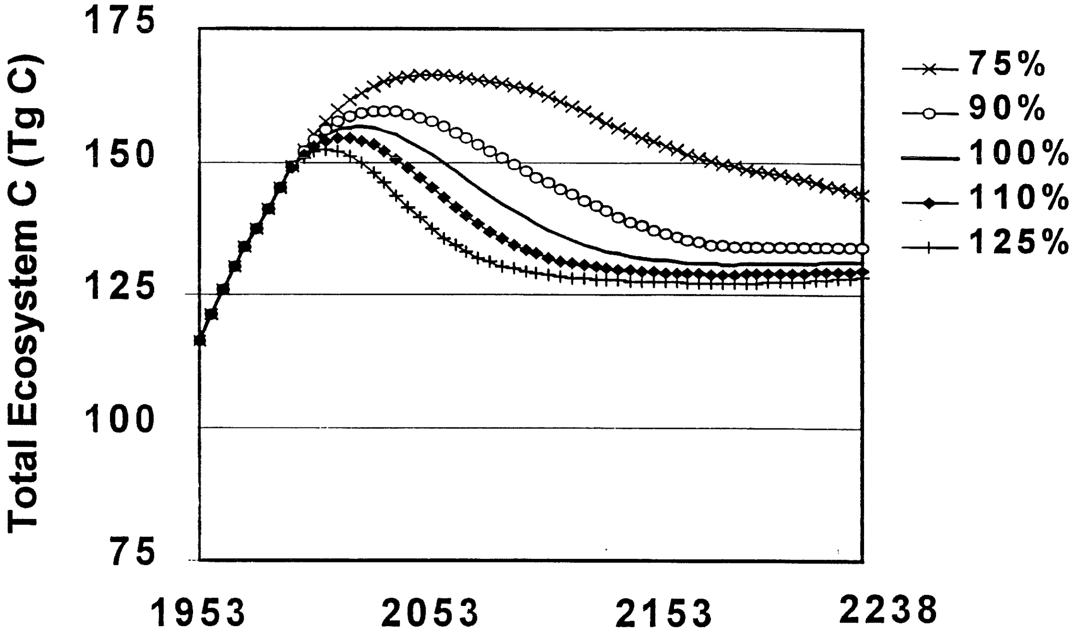


Fig. 9. Results of sensitivity tests to assess the effects of different disturbance cycles on total ecosystem C storage in the Foothills FMA area. Thick lines without symbols represent unmanaged scenarios (from Fig. 5); thin lines with symbols represent managed scenarios (from Fig. 4).

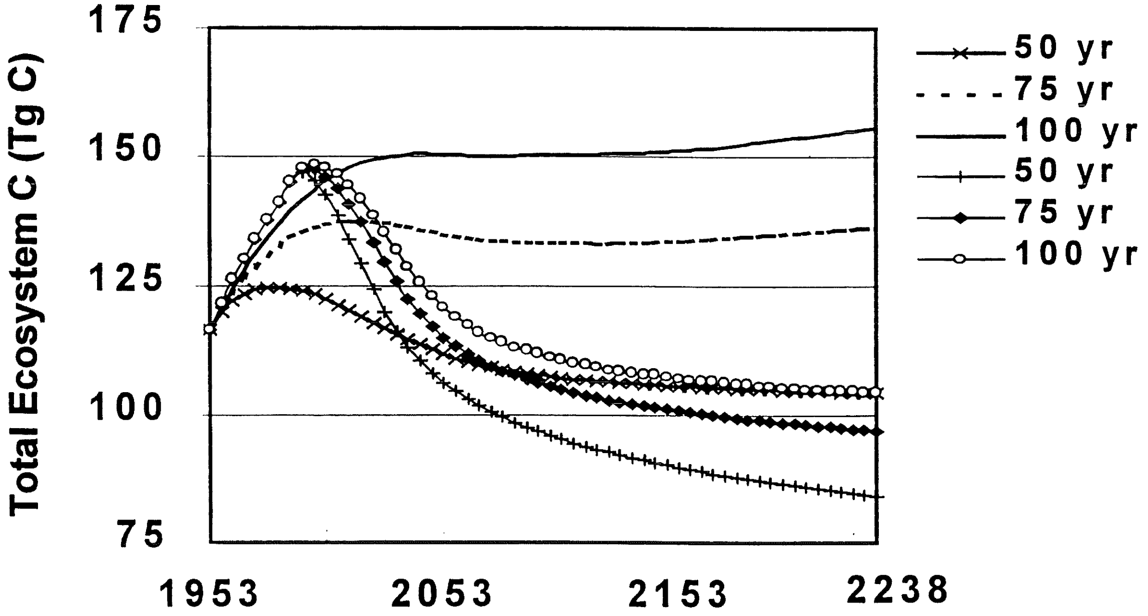


Table 2. Results of sensitivity tests on projected estimates of total ecosystem C simulated by CBM-CFS2 for the Foothills Forest FMA area. The percentage changes (gains and losses in total ecosystem C pool size) are expressed relative to the managed and unmanaged baseline scenarios, as indicated.

Date	**2003**		**2053**		**2103**	
	Tg C	%	Tg C	%	Tg C	%
Managed Scenarios						
A0. Baseline C pool size	154	(100)	151	(100)	137	(100)
A1. Harvesting at 75% of planned	+1.6	+1.1	+14.9	+9.6	+25.1	+17.8
A2. Harvesting at 90% of planned	+0.7	+0.4	+6.2	+4.0	+8.8	+6.2
A3. Harvesting at 110% of planned	-0.7	-0.4	-6.2	-4.0	-5.3	-3.8
A4. Harvesting at 125% of planned	-1.7	-1.1	-13.9	-9.0	-8.5	-6.1
A5. 100% Harvest + Silviculture	+0.1	+0.1	+5.7	+3.7	+19.0	+13.5
100% Harvest + Disturbances since 1953 with:						
A6. 50-year cycles	-11.0	-7.1	-45.2	-29.1	-42.1	-29.9
A7. 75-year cycles	-7.4	-4.8	-36.4	-23.5	-32.4	-23.0
A8. 100-year cycles	-5.6	-3.6	-30.6	-19.8	-26.7	-19.0
Unmanaged Scenarios						
B0. Baseline C pool size	122	(100)	112	(100)	107	(100)
Disturbances only since 1953 with:						
B1. 75-year cycles	+14.6	+12.7	+23.3	+20.3	+26.0	+24.1
B2. 100-year cycles	+23.0	+20.1	+38.7	+33.8	+43.4	+40.2
B3. Soil decomposition at 75%	+9.3	+8.2	+13.2	+11.6	+15.7	+14.5
B4. Soil decomposition at 125%	-6.4	-5.6	-8.9	-7.8	-10.6	-9.9
Baseline Gain from Management (assuming FMP projections)	+32	+25.7	+39	+35.5	+30	+28.1

Table 2 shows results of sensitivity tests on total C stocks (including wood products C for those scenarios involving harvesting) in the entire FMA area, projected for 50, 100 and 150 years beyond 1953. As also seen from Fig. 7, gains from stand density control would lead to significant increases in total C storage, in the longer term (about 13% after 150 years). Decreases in estimated C storage resulting from underestimating soil decomposition rates are about 10% after 150 years, an error which continues to increase for the duration of the simulation. Such errors produce significant changes in the long term estimate of absolute total C storage, but the relative errors in results for the managed scenarios should be similar. Table 2 also summarizes the net gains in total C storage resulting from management, as the differences of the two baseline scenarios. Scenario A0 results in approximately 25% greater C stored in the system after 50 years, increasing to about 35% after 100 years but then declining to about 28% after 150 years.

Discussion

Although they differ in absolute terms, the results of this study are consistent with those reported by Price et al. (1996). The earlier study indicated greater stocks of C under all scenarios throughout the simulation period, and larger increases due to management. The discrepancies are readily explained, however, by the use of an incomplete data base in the earlier study, and the associated assumption of uniform distributions of stand productivity for the unmapped areas. The present study uses a complete data base and a better representation of the differences among the four ecoregions found in the Foothills FMA area. In addition, the effects of the known history of disturbances since 1953 were taken into account, and found to reduce the estimates of total C stocks by about 3% in 1988.

This study clearly demonstrates that managing a forest for wood production may lead to greater C storage than occurs in the natural forest ecosystem. This result, however, is likely to apply only to those areas of the boreal and other forest ecosystems where natural disturbances are more frequent than the MSY rotation length. Hence, our results do not contradict those of Harmon et al. (1990) who report decreased C storage in second-growth forests of the Pacific North West—

primarily because the managed rotation length in such forests is often considerably shorter than the natural life-span of the unharvested forest ecosystem.

With a single exception (Fig. 7), all the managed scenarios caused biomass C stocks to decline to steady mean densities of about 20 Mg C ha^{-1} in the long term (ca. 2100 onwards). This indicates that in C storage terms, planned harvesting levels will not be sustainable unless anticipated productivity gains are achieved from stand density control following harvesting. Non-sustainability of biomass C storage due to harvesting does not necessarily imply non-sustainability in terms of timber production: silvicultural practices may increase the proportion of utilizable timber while not affecting (or even reducing) biomass productivity. In C terms, it is important to look at the consequences of management on total C storage—including that contained in vegetation, soils and wood products.

Scenario A5 assumes that volume-to-biomass ratios for fire-origin stands are applicable to respaced stands of harvest-origin. This could be a serious error. Some studies suggest that aboveground biomass productivity in lodgepole pine also increases at lower stem densities: e.g., Pearson et al. (1984) observed lower root-to-shoot biomass ratios, and greater aboveground biomass; Keane and Weetman (1987) reported greater leaf area index, and increasing sapwood area to leaf area ratio (both of which would support greater biomass productivity). Kimmins (University of British Columbia, 1988, pers. comm.) has suggested that very dense stands may invest a very high proportion of photosynthate in fine root turnover in order to compete for limited soil nutrients and water, with the result that very little aboveground biomass accumulation occurs. Clearly, this issue has important implications for estimates of C storage in forest biomass. Changes in the volume-to-carbon ratio for projected forest growth will significantly affect the overall C estimate, particularly if the primary forest is steadily harvested and replaced by stands of much lower stem density.

This study recognizes that the contribution of wood products to total C storage varies with the harvest level achieved, leading to greater differences among the managed scenarios. In particular, when productivity gains from silviculture are included (scenario A5), greater amounts of C appear in the products pool as well as in the biomass and soil pools (Figs. 4, 6 and 7). The steady accumulation of C in landfills with a very slow decay rate is the primary contribution to long term storage. Carbon contained in pulp and lumber products stabilizes relatively quickly because their average life-spans are relatively short.

Projected long-term increases in C storage are based on several key assumptions concerning disturbances and management practices. First, the net C releases due to consumption of fossil fuel (and offset in bioenergy and avoided emissions) have not been estimated in detail for the Foothills Forest area but preliminary estimates suggest that they presently make only relatively small contributions to the overall budget. The conclusions drawn here should remain valid provided that changes in energy consumption associated with changed levels of harvesting and protection are not significant. Second, all harvested areas are implicitly assumed to regenerate promptly; Kurz et al. (1995) show this has a relatively small, one-time influence. Third, projected increases in aboveground biomass resulting from stand density control following harvesting are postulated (but remain to be verified) for the best-case managed scenario.

The remaining key assumptions, dealing with disturbances and the environment require more discussion. The analysis performed here uses a natural disturbance cycle of 50 years, as reported in the published literature (Van Wagner 1978). Recent work (E. Johnson, University of Calgary, 1997, pers. comm.) suggests that the 50-year cycle may be a significant underestimate. A longer natural disturbance cycle would lead to higher C storage and hence smaller gains (or even losses) due to management. In addition, the management scenarios assume that natural disturbances (fires and pathogen attacks) can be completely suppressed. A related issue—that of assumed unchanging environmental conditions—must be considered.

It has been argued that maximum short-term C storage benefits are obtained by allowing forest ecosystems to achieve maximum biomass (Nabuurs 1996; Schlamadinger and Marland 1996; Fischlin 1996). For the boreal forests of western Canada, where annual productivity is generally low and the risk of natural disturbances is high, the cost of protection needed to obtain maximum biomass is difficult to justify for the sake of C sequestration alone.

Protection is more justifiable when its costs can be offset by the benefits of harvested timber and other forest values. Where protection extends the average life-span of the forest, it leads to a higher proportion of older stands, and an increase in average biomass C density. Greater biomass leads to increased transfers of litter to the soil and greater total ecosystem C storage. Harvesting also transfers a portion of the biomass C into wood products both reducing the combustible material left on site and increasing the wood products C pool. Whether or not these mitigate atmospheric GHG concentrations depends on whether the average life-span of the wood C contained in buildings, landfills and slash is longer than that of the C stored in unharvested trees and their natural litter (Hendrickson 1994).

Harvest rotation length also influences C storage in the ecosystem (Fig. 8 and Table 2). Although shortening the rotation length from MSY reduces timber yield, it decreases timber losses to fire and may also reduce protection costs. A shorter rotation reduces average biomass density (per unit of forest area) and the quantity of larger dimension wood products (with longer average C retention). Figure 8 shows that reducing the rotation length (increasing harvest level) causes a relatively small reduction in total ecosystem C storage. This is partly because, as the baseline scenario shows, planned harvesting levels appear non-sustainable in the absence of silviculture.

Conversely, comparable reductions in harvesting level lead to quite significant increases in total C storage, because they allow greater average C densities to persist in the forest biomass. The resulting product mix also favours a higher proportion of longer lived products. (In this study the proportions of pulp and lumber products were considered fixed.)

Some of the previous conclusions are subject to the consequences of a changing climate. Recent reports indicate that climate change due to anthropogenic perturbations to atmospheric GHG concentrations is already detectable. Although reliable projections for the study area do not exist, Houghton et al. (1996) warns that the most significant changes are to be expected in the mid-continental northern hemisphere. From a review of published literature on forest ecosystem responses. Kirschbaum and Fischlin (1996) conclude that boreal forests would be the most severely affected by these changes.

One expected effect of a warmer boreal climate is increased disturbances, due particularly to insect attacks and fires (Bergeron and Flannigan 1995; Stocks et al. 1996; Volney 1996). Under such circumstances, forest protection costs would increase significantly, making shorter timber rotations more economically attractive. Figure 9 strongly suggests that protection of the harvested forest will be obligatory if the system is to retain as much C as the unmanaged system. The long-term benefits of management for C storage projected for the Foothills FMA are contingent upon suppression of natural disturbances—to an average cycle of 100 years or longer—although salvage harvesting and improved timber utilization could help to relax this requirement.

Climate change may also affect forest productivity, through both direct effects on physiology, seed production and germination success, and indirect effects on the population behaviour of endemic insect pests and disease organisms (Kurz et al. 1995b; Fleming and Volney 1995). Although such effects have yet to be explored for the Foothills Forest with CBM-CFS2, they would likely cause similar trends in the C dynamics of both managed and unmanaged ecosystems. In reality, it is likely that managed ecosystems would lose less C under a warmer climate, because management practices—including protection against fire and insect attack—are aimed at maximizing wood production. This study shows that systematic increases in soil decomposition rates (also expected under a warmer climate) would lead to significant reductions in long-term ecosystem C storage, similar in magnitude to the expected long-term benefits of management. Even so, such losses would be expected under both managed and unmanaged scenarios.

Conclusions

Forest management practices in the region of the Foothills Forest appear to have contributed to an increase in total carbon storage because the typical managed stand rotation age is longer than the reported 50-year average cycle of stand-replacing natural disturbances in the absence of management. This increase is likely to be sustained in the future under all management scenarios where protection efforts are largely successful. Net reductions in total C storage will occur if planned levels of harvesting are maintained without suppression of natural disturbances. These findings imply that management and harvesting of forest ecosystems characterized by frequent natural disturbances may actually be more beneficial for sequestering atmospheric C than preservation of the natural ecosystem. This contrasts with earlier findings of lower C storage in managed forests compared to the natural ecosystems they replace; the primary explanation for this apparent contradiction is that many forests reach natural stand ages much greater than the typical managed rotation age, thereby achieving greater ecosystem C storage.

For the Foothills Forest, the projected overall gains in total ecosystem C storage expected from planned management are approximately 25% and 35% after 50 and 100 years respectively. These estimates are based on the assumptions that no gains in average biomass productivity can be achieved through silvicultural treatments, and that fossil fuel emissions associated with management operations are small compared to the net uptake of CO_2 by the forest. Although no allowance for the effects of a warming climate has been made in this study, any resulting impacts would likely affect both managed and unmanaged ecosystems similarly.

Sensitivity tests show that total ecosystem C storage would increase quite significantly if future harvesting levels were to be reduced by 25%, mainly because the areal proportion of older stands would be increased. The economic justification for such a strategy depends upon the cost of protecting stands for additional years, balanced against the value society places on non-timber benefits including the additional C sequestered in the ecosystem.

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