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

D.T. Price, D.H. Halliwell, M.J. Apps, W.A. Kurz, and S.R. Curry

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 with 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 as a result of 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.

Résumé : Un modèle de bilan du carbone du secteur forestier canadien (CBM-CFS2) a été modifié afin d'examiner les impacts possibles, passés et futurs, des pratiques d'aménagement sur la séquestration de C dans la biomasse forestière, les sols et les produits forestiers récoltés dans une unité d'aménagement forestier des écorégions boréale–cordillérenne de l'Ouest du Canada. Le modèle a montré que la suppression totale des perturbations naturelles et leur remplacement par une récolte pour un rendement soutenu maximum pourrait conduire à des accroissements significatifs du stockage de C dans l'écosystème (principalement dans les sols et les produits forestiers) sur une période de 100–200 ans dans cette région. Ceci est préliminaire en raison de l'intervalle historique court entre les événements perturbateurs (surtout les feux naturels) lorsque comparé à l'intervalle de récolte. Les gains nets dans le stockage de C et la période sur laquelle ils sont soutenus, sont sensibles à plusieurs variables clés, incluant les niveaux prévus de récolte et l'intensité des perturbations naturelles. Un climat plus chaud pourrait réduire le stockage de C dû à une décomposition plus rapide dans le sol mais cela ne devrait pas renverser les bénéfices attribuables à l'aménagement si les perturbations sont contrôlées. Accroître la longueur des rotations augmente significativement le stockage total de C et peut justifier un investissement additionnel pour la protection.
[Traduit par la Rédaction]

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 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

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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- to 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 database 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 with 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. First, how do forest protection, silvicultural treatments, and operational harvesting affect C sequestration in a managed forest? Second, 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 1.2×10^6 ha, mainly in the Upper and Lower Boreal–Cordilleran, but including small proportions in the Sub-alpine and Montane ecoregions (Alberta Forestry, Lands and Wildlife 1992). Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) is the dominant species in stands covering 65% of the land area. White and black spruces (*Picea glauca* (Moench) Voss and *Picea mariana* (Mill.) BSP) are dominant in a further 20%, while aspen (*Populus tremuloides* Michx.) is dominant in mixedwoods covering much of the remaining area. The annual average temperature in this region, estimated from 1961 to 1990 normals for local climate stations (Atmospheric Environment Service 1993), is 2.4°C. Average soil C density for the Cordilleran ecoregion is estimated to be 84.3 $\mathrm{Mg\,C{\cdot}ha^{-1}}$, derived from the Canadian Forest Service soil C database (Siltanen et al. 1997).

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 relationships. The effects of disturbances (principally wildfires, insect attacks, and harvesting) on forest age structure and on C releases to the atmosphere and forest floor are calculated on a 5-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 among 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 ($\mathrm{m^3{\cdot}ha^{-1}}$) 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 years. For stands reaching maximum volume before age 100 (typically aspen), the mature phase was considered to last until age 160 years. Following the mature phase, stand breakup was represented by a negative exponential with decay rates of 0.01 $\mathrm{year^{-1}}$ and 0.02 $\mathrm{year^{-1}}$ for conifers and hardwoods, respectively. Natural disturbance and harvesting intervals are typically in the range 50–100 years, so an imperfect representation of stand breakup 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 database (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 stems/ha). 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 C 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. 1995*b*).

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 2×10^6 $m^3 \cdot year^{-1}$ for the 20-year period 1988–2007, of which 1.9×10^6 $m^3 \cdot year^{-1}$ are expected from coniferous stands. Certain operational constraints are specified in Weldwood's FMP. First, stands must carry a minimum of 47.5 $m^3 \cdot ha^{-1}$ of merchantable conifer timber to be considered operable. Second, the annual harvest is determined by the need for a sustained wood supply of 2×10^6 $m^3 \cdot year^{-1}$; hence areas harvested and regenerated annually may vary. Third, current harvesting is concentrated on stands that 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. Fourth, 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 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) or 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, personal communication). 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 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 with 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 base-line 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 base-line 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.

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. Base line: 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 years starting 1953	Harvesting as recorded since 1953
A7. Natural disturbances with average cycle of 75 years starting 1953	Harvesting as recorded since 1953
A8. Natural disturbances with average cycle of 100 years starting 1953	Harvesting as recorded since 1953; closest to observed natural disturbance cycle in 1988†
A9. Natural disturbances with average cycle of 50 years starting 1988	Assume no disturbances prior to 1988; harvesting as recorded
A10. Natural disturbances with average cycle of 75 years starting 1988	Assume no disturbances prior to 1988; harvesting as recorded
A11. Natural disturbances with average cycle of 100 years starting 1988	Assume no disturbances prior to 1988; harvesting as recorded
(B) Unmanaged, no harvesting, from 1953	
B0. Base line: natural disturbances on 50-year cycle	No management or harvesting
Sensitivity tests	
B1. Increase natural disturbance cycle to 75 years	No management or harvesting
B2. Increase natural disturbance cycle to 100 years	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.

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 base-line 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 base-line 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

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 Fig. 1*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 Fig. 1*b*.

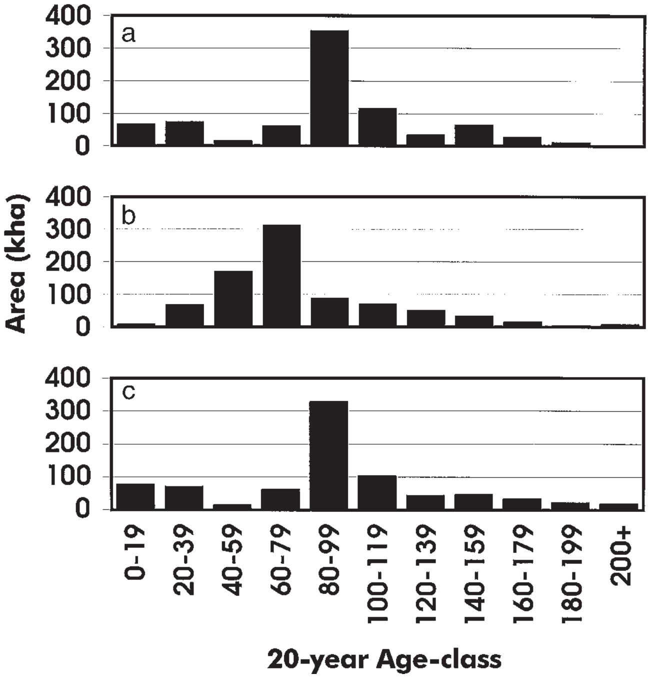
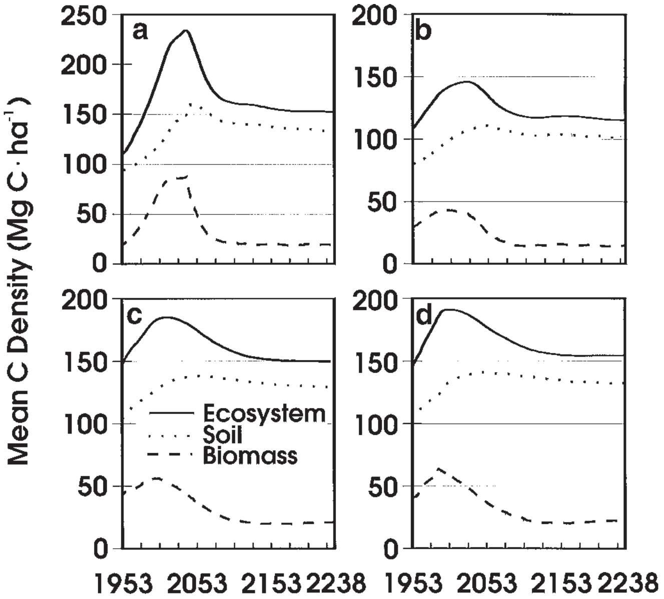


Fig. 2. Carbon budget simulation results for four ecoregions in the Foothills Model Forest forest management agreement (FMA) area, based on the reconstructed age-class distribution for 1953 (Fig. 1*b*). The simulations assumed the known history of harvesting for the period 1953–1988 and planned future 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*) Subalpine (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.



changed by ±25% (B3 and B4) relative to those used in the base-line unmanaged scenario (B0).

Results

Figure 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.

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 with the managed scenario of Fig. 2. The long-term trends lead to equilibrium in biomass C densities (which interestingly are virtually identical with 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

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

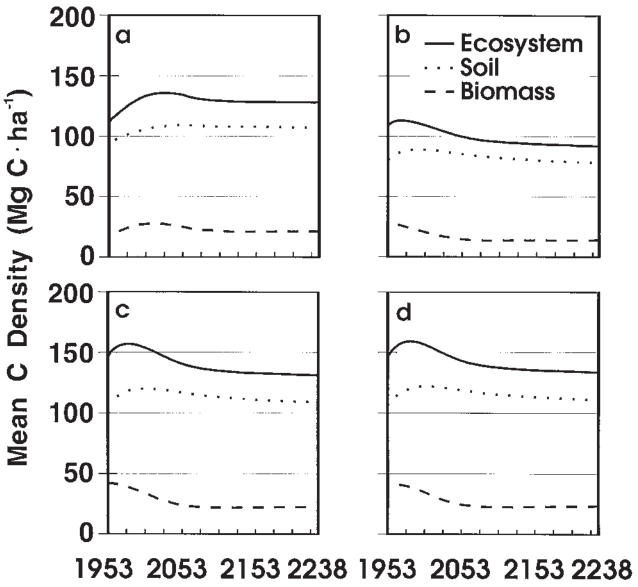
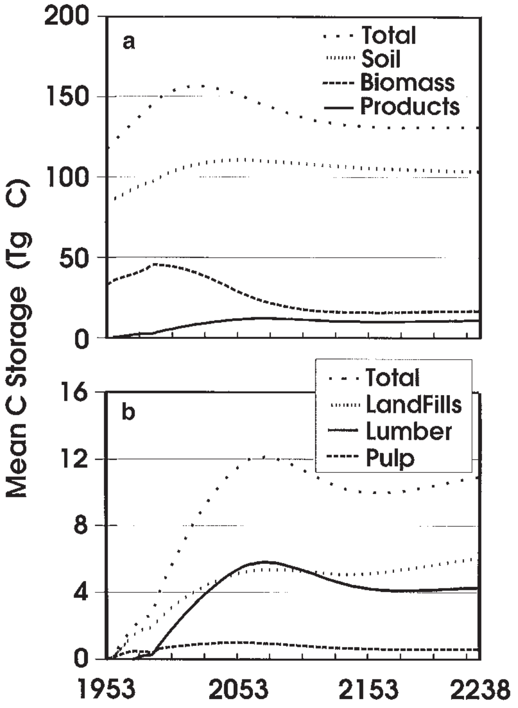
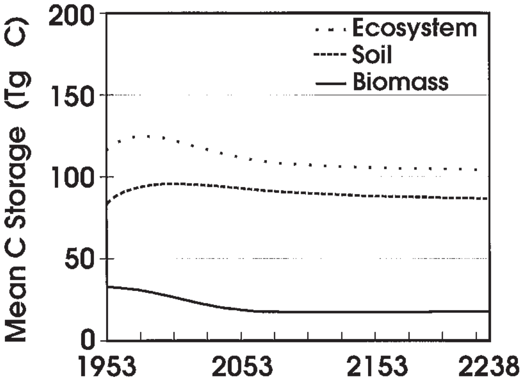


Fig. 4. (*a*) Simulated changes in C storage in soils, biomass, wood products, and total forest ecosystem for the Foothills FMA area (820 657 ha), under the managed scenario of Fig 2. (*b*) Details of C storage in pulp products, lumber products, and landfills for the wood products pool changes shown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



indicates that before 1953, the average disturbance cycle in this ecoregion was only slightly longer than 50 years.

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



Results for individual ecoregions (Figs. 2 and 3) are summed (Figs. 4*a* 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. 4*b* shows the contribution of manufactured wood products (pulp, construction lumber, and material disposed in landfills). Scenario A (Fig. 4*a*) results in greater total C storage at all times, reaching a peak close to 160 Tg C around 2005, compared with 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, compared with 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.

Figure 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 with 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 with the worst-case (i.e., no productivity gains) 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*).

Figure 8 compares the effects on total ecosystem storage of varying future harvesting by ±10% and ±25% of the planned

Fig. 6. (*a*) As for Fig. 4*a*, but for a managed scenario that 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*) Details of C storage in pulp products, lumber products, and landfills for the wood products pool changes shown in Fig. 6*a*.

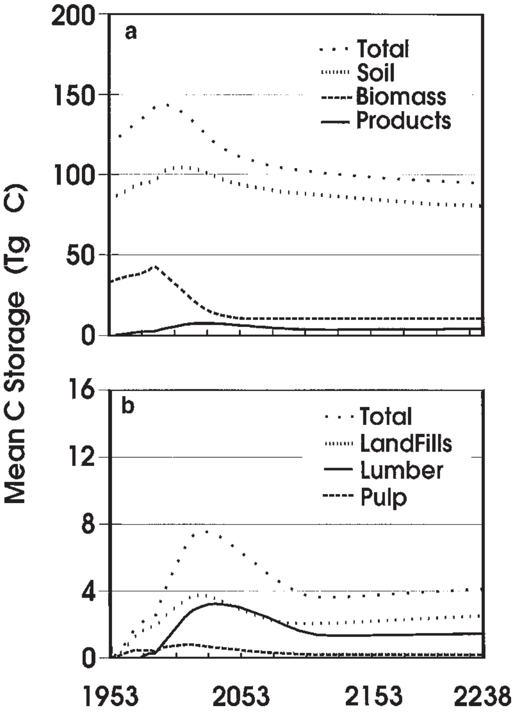
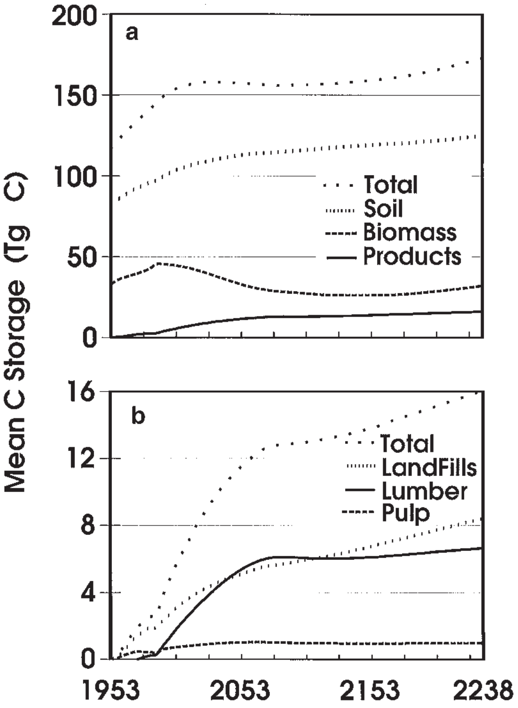


Fig. 7. (*a*) As for Fig. 4*a*, but for a best-case managed scenario that accounts for productivity gains resulting from the effects of stand density control following harvesting. (*b*) Details of C storage in pulp products, lumber products, and landfills for the wood products pool changes shown in Fig.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



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.

Figure 9 compares natural disturbance cycles of 50, 75, and 100 years, for both unmanaged (base-line, 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 years in 1953, and to 93 years 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.

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 that 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 base-line 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 database in the earlier study, and the associated assumption of uniform distributions of stand productivity for the unmapped areas. The present study uses a complete database 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

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

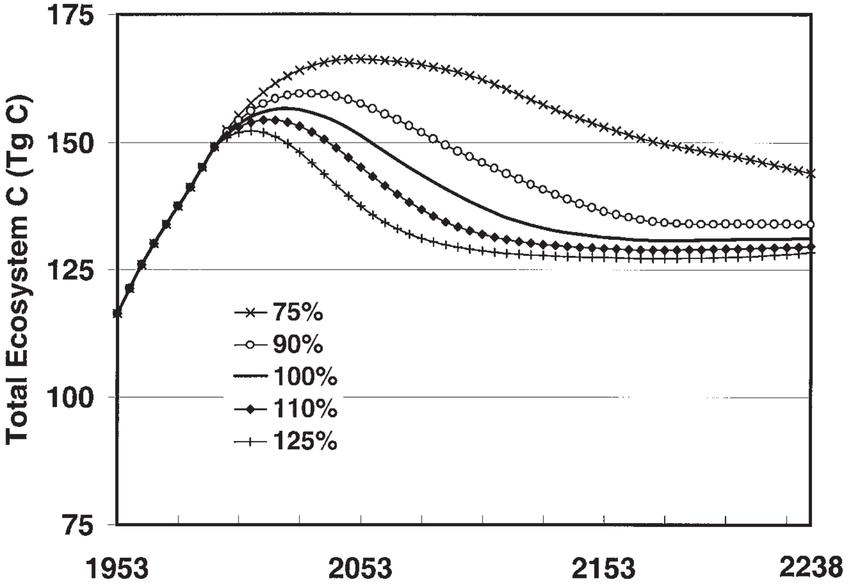
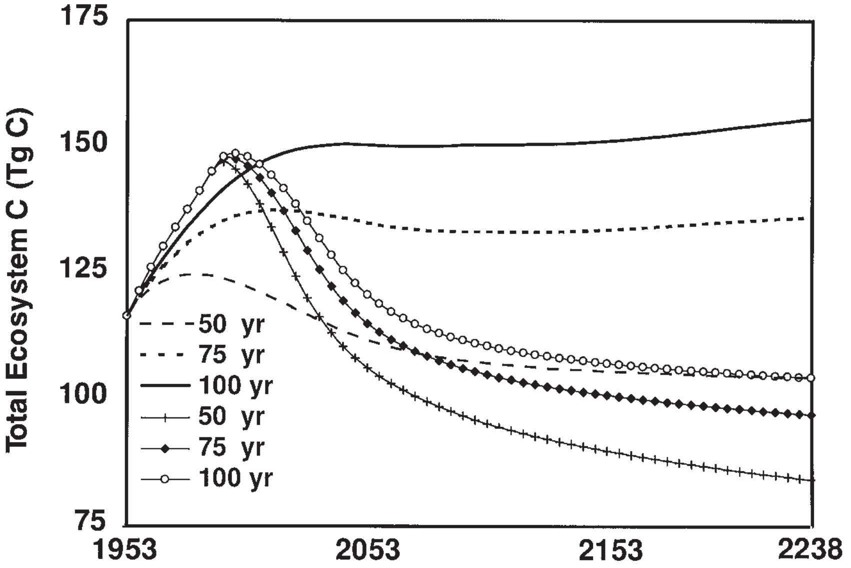


Fig. 9. Results of sensitivity tests to assess the effects of different disturbance cycles on total ecosystem C storage in the Foothills FMA area. Thick lines without symbols represent unmanaged scenarios (from Fig. 5); thin lines with symbols represent managed scenarios (from Fig. 4).



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. Nonsustainability of biomass C storage due to harvesting does not necessarily imply nonsustainability 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

Table 2. Results of sensitivity tests on projected estimates of total ecosystem C simulated by CBM-CFS2 for the Foothills Forest FMA area.

	2003		2053		2103	
Date	Tg C	%	Tg C	%	Tg C	%
Managed scenarios						
A0. Base-line 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. Base-line 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
Base-line gain from management (assuming FMP projections)	+32	+25.7	+39	+35.5	+30	+28.1

Note: The percent changes (gains and losses in total ecosystem C pool size) are expressed relative to the managed and unmanaged base-line scenarios, as indicated.

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, personal communication) 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*a*) 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, personal communication) 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 these mitigate atmospheric greenhouse gas 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 1990).

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 base-line scenario shows, planned harvesting levels appear nonsustainable 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 greenhouse gas 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 midcontinental 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. 1995*c*; 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 with 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 with 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 nontimber benefits, including the additional C sequestered in the ecosystem.

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