23 Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study

David T Price, Ralph M Mair, Werner A Kurz[1] and Michael J Apps

Natural Resources Canada, Canadian Forest Service, Northwest Region,
Northern Forestry Centre, 5320 - 122 Street, Edmonton, AB T6H 3S5, Canada

INTRODUCTION

Many northern forests are managed with the objective of achieving and maintaining sustained yield. Sustained yield management implies continuous production so planned as to achieve at the earliest practical time, a balance between annual growth and harvesting. It is often argued that with silvicultural prescriptions, and protection from natural disturbances, responsible management will allow wood harvests and other benefits to be elevated in the long term, and thereafter maintained at increased levels indefinitely (when compared to unmanaged forest growing in a similar environment).

Taking this optimistic perspective, what are the likely impacts on the global carbon (C) balance of practising maximum sustained yield harvesting on a global scale? To answer this question it is necessary to account for the steady annual processing of harvested materials into wood products (i.e., manufactured goods ultimately derived from harvested trees), and their subsequent incineration or disposal in landfills. A working hypothesis would be that in the long term, assuming no changes in average climate, the annual global releases of C from decay and consumption of old wood products must eventually balance the annual additions of C from newly manufactured forest products (assuming the yield can be sustained), i.e., the net rate of accumulation of C in the forest products pool must tend asymptotically to zero. When this happens, the global product pool reaches a maximum: it may be said to be saturated.

The net accumulation of C in forest products that will take place until saturation occurs represents a finite potential sink for atmospheric CO_2. What is the capacity of this sink and how long will it last? Placing an upper limit on the value of this sink could be useful for developing global policy on the use of forests for mitigation of greenhouse gas (GHG) emissions. Additionally, wood could be used as a renewable energy source (which does not prevent other uses before burning it), in which case the energy value could also be used as an offset against emissions from fossil fuel energy production. What is the global maximum possible magnitude for this offset?

It is not currently possible to assess fully the dynamics of the global forest products pool, and how these dynamics relate to the conceptual management objective of maximum sustained yield applied to the world's forests. An alternative approach is to use individual forests as case studies, and possible models for the global picture. This is the approach adopted here, using a single forest management unit in central Alberta.

1 ESSA Technologies Ltd., 3rd Floor, 1765 West 8th Avenue,
Vancouver, B.C., V6J 5C6, Canada

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This paper examines some aspects of boreal forest C dynamics under a small range of defined future scenarios, and reports on the expected changes in C storage that would result under each of these assumed scenarios. The focus is on the roles of forest management and the forest product C pool in altering net C storage compared to the unmanaged and unharvested ecosystem. Specifically, it will address the following questions:

1. How does operational harvesting affect C sequestration in a managed forest, as compared to leaving it in an unexploited state?
2. What is the approximate time required to saturate the local forest products C pool, assuming the management objective of maximum sustained yield harvesting can be achieved?
3. What limits the size and duration of the local forest products sink?
4. What is the magnitude of the C emission offset if all products are also used for energy production?
5. Can insights obtained from the local analysis be extended to the global scale?

METHODS

C budget model

A simulation experiment was carried out for the forest management agreement (FMA) area of the Foothills Forest located in west central Alberta (Price et al. 1994) using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). The model, described extensively elsewhere (e.g., Kurz et al. 1992; Apps and Kurz 1994; Kurz and Apps 1994), uses data derived from forest inventories, ecosystem classification, soil surveys and forestry statistics from government and industry, to estimate the C content of three distinct pools: biomass, soils and products. It uses empirical equations to simulate annual forest growth and soil decomposition for representative stand-types, while disturbance effects (including harvesting) are assessed over longer timesteps (typically five years). In previously reported assessments, CBM-CFS has been used to estimate forest sector C budgets for Canada as a whole (Kurz et al. 1992; Apps and Kurz 1994; Kurz and Apps 1994), and for specific ecoregions of Canada (e.g., Chapter 14; Apps et al. 1993; Kurz and Apps 1993).

This paper reports three simulation experiments using the dynamic version of the model (CBM-CFS2) to perform comparative C budget analyses of the Foothills FMA area. In the first simulation (Experiment I), only the effects of natural ecosystem processes on the forest sector C budget were examined for a 230-year period beginning in 1958 (taken to be the start of active management operations). It was assumed that there was no human intervention, that a natural 50-year disturbance interval persisted for the period prior to 1958, and that no changes in average environmental conditions occurred since then. In the second experiment (Experiment II), the effects of harvesting and management as practised by the current FMA licensees, Weldwood of Canada, on forest C dynamics were examined for the same 230-year period. This scenario assumed that yield projections would be met and that natural disturbances could be completely suppressed. Annual harvesting rates were assumed to be those for the known past (based on areas regenerated since 1958) and for the projected future from 1988 onwards (based on planned harvests). Management assumptions included increased site productivity following harvesting, (anticipated from Weldwood's silvicultural prescriptions), and no change in environmental conditions. A third experiment (Experiment III) examined the consequences of failing to achieve these projected yield increases, but again assuming complete suppression of natural disturbances.

Site description

Covering approximately 1.2 Mha, Foothills Forest is one of ten "model forests" established within Canada to promote sustainable development and integrated management of Canada's forest resources. The dominant species are lodgepole pine (*Pinus contorta* Dougl.), black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*Picea glauca* (Moench) Voss.) and aspen (*Populus tremuloides* Michx.). In addition to pest control and suppression of wildfires carried out over the entire area, approximately 800 000 ha are considered operable, where harvesting and silviculture are practised. Silvicultural treatments include: stand tending of white spruce stands following removal of aspen overstorey; selective logging on sensitive sites; scarification to promote natural seeding or prior to artificial seeding or planting; brush and weed control; and juvenile spacing of lodgepole pine stands (Weldwood 1992). A systematic coverage of about 3000 permanent growth sample plots (PSPs), dating back to the mid-1950s, is maintained. The data from these plots are used to develop local yield models for calculating and updating projections of annual harvest volumes. Virtually all harvested timber is supplied to local pulp and sawmills, which produce only kraft pulp, construction lumber and particle board.

Information on local ecosystem C was derived from previously estimated parameters for the Upper and Lower Boreal–Cordilleran ecoregions in which almost all of the productive portion of the Foothills FMA area is located (Alberta Forestry, Lands and Wildlife 1992). Soil C density in the FMA area was estimated to be 84.3 Mg C ha^{-1}, based on the average for the Cordilleran ecoregion contained in the Canadian Forest Service soil C data base (Siltanen et al. 1995).

Disturbances

The age-class structure of the Foothills Forest, as observed in 1988, is shown in Figure 23.1. No significant harvesting occurred before management began in the mid-1950s, and since then, there have been few losses to fires or insect attack. Hence, the areas in the 0 to 30-year age classes represent, almost exclusively, those regenerated following harvesting, averaging about 4500 ha yr^{-1}. It was therefore possible to estimate the age-class structure of the forest as it existed in 1958, assuming that the older age classes were harvested in proportion to their area in the forest at that time.

The CBM-CFS2 was then initialised using this reconstructed age-class structure, and run forward in time from 1958 for 230 years. Van Wagner (1978) provides estimates of the mean disturbance interval derived for stands in the area of the Foothills FMA (referred to in his paper as "the forest of Northwestern Pulp and Power Ltd."). He found that prior to ca. 1915, the mean disturbance interval was approximately 50 years, but during the period 1915–1960, it increased to approximately 65 years, presumably in response to fire suppression practices in the area.

Biomass carbon pool

Kurz et al. (1992) used aboveground biomass inventory data collected by Bonnor (1982, 1985), to develop relationships between stand age and dry biomass (referred to as "biomass over-age" curves), for 457 forest stand-types distributed across Canada (Kurz and Apps 1994). These curves differentiate four distinct phases of forest biomass accumulation: regeneration delay, immature (growth), mature and overmature (where "stand-break-up" may occur).

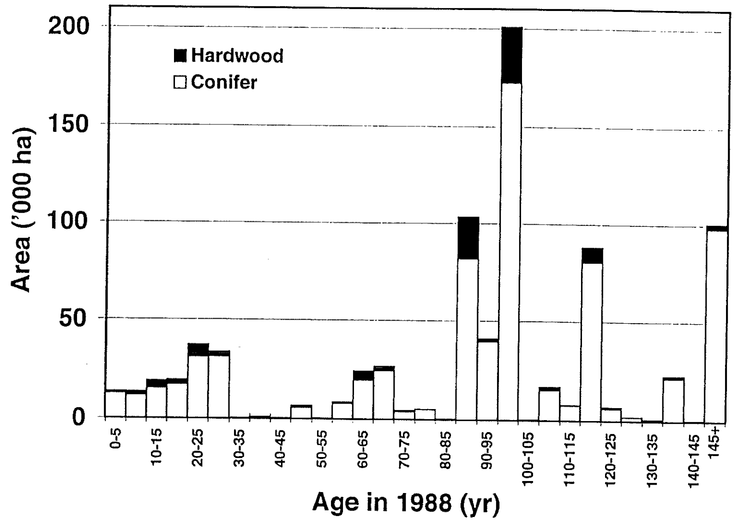

Figure 23.1. Age-class structure of the Foothills Forest determined from 1988 forest inventory data (Weldwood 1992).

For the analysis reported here, the Weldwood PSP data were used to parameterize the CBM-CFS2 biomass-over-age curves for the Foothills FMA area. Weldwood's 1991 Detailed Forest Management Plan explains how growth measurements obtained from the PSPs are used to derive approximately 70 volume yield curves (YCs), considered to represent the range of growing stock conditions within the FMA area (Weldwood 1992). Each stand identified in the forest inventory is matched to one YC, of which 56 are applicable to operable areas. The Weldwood YCs provide separate data for the softwood and hardwood components of each stand-type, reported as merchantable timber volumes (m^3 ha^{-1}) at 10-year intervals ranging from 10 to 150 years, after which they are assumed to remain constant. The approach adopted was therefore, firstly to transform the data for each YC into an equivalent biomass-over-age curve for use by CBM-CFS2; and secondly to estimate the C dynamics of forest biomass in the Foothills Forest using Weldwood's stand inventory data. The inventory data, contained in a GIS data base of over 300 000 records, were aggregated into 56 stand-types, corresponding to each YC. The Weldwood GIS inventory covers only about 50% of the FMA area, but was considered extensive enough to be representative of the entire area-weighted age-class distribution (Figure 23.1).

The data were used to estimate the dry biomass for each 10-year age class from its volume equivalent, using species-specific merchantable volume-to-biomass conversion equations for central Canadian species (Singh 1984). The CBM-CFS2 biomass-over-age curves were then fitted to the biomass yield data. A fixed regeneration delay of five years was assumed, after which the immature growth phase was fitted to a logistic growth function. For YCs where maximum biomass was reached after 100 years (typically conifers), the mature phase was generally considered to last from 150 to 200 years, with the biomass at 150 years being maintained until 200 years. For stands reaching maximum volume before 100 years (typically aspen), the mature phase was considered to last until 160 years. Following the mature phase, stand break-up was simulated using a negative exponential with a decay rate of 0.01 yr^{-1} for conifers and 0.02 yr^{-1} for hardwoods. With natural disturbance and harvesting intervals of order 50–75 years, the representation of the stand break-up phase is expected to have little impact on estimated C dynamics. Figure 23.2 shows a typical example of a CBM-CFS2 biomass-over-age curve fitted to a Weldwood YC.

The productivity of many sites is expected to increase significantly following harvesting of older stands. This occurs because lodgepole pine stands of fire-origin often achieve such high stem densities (sometimes exceeding 100 000 stem ha^{-1}) that volume growth stagnates within a few years (Pearson et al. 1984; Keane and Weetman 1987; Tait et al. 1988). The density of stands regenerated following harvesting can be controlled, leading to significantly improved merchantable volume production (often as much as 50% increase). Relatively few studies however, report corresponding increases in aboveground biomass productivity. With decreasing stand density, Pearson et al. (1984) observed lower root: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). The hypothesis has been advanced that very densely stocked stands invest a very high proportion of photosynthate in fine root turnover in order to exploit limited soil nutrients and water, with the result that very little aboveground biomass accumulation occurs (JP Kimmins, University of British Columbia, 1988, pers. comm.).

Weldwood represents increased volume growth in lodgepole pine stands regenerated following harvesting by allocating new YCs. Since there is some question about the impacts of density control on biomass productivity, it may be incorrect to assume that the volume-to-biomass ratios determined for fire-origin stands will also be appropriate for those where silvicultural treatments have been applied. The significance of this will be discussed later.

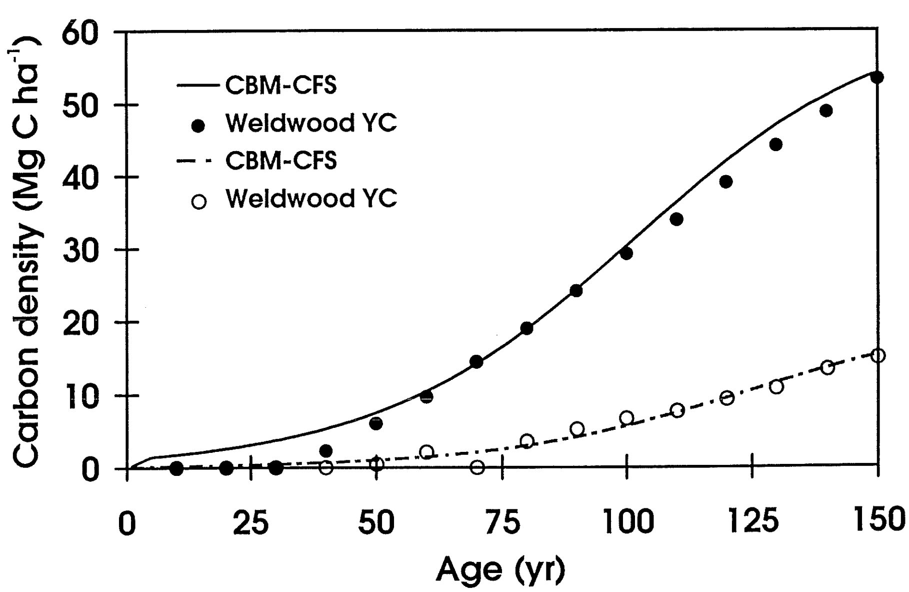

Figure 23.2. Example of a Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) biomass-over-age curve fitted to a Weldwood Yield Curve (YC) for the Foothills Forest. Volume data for softwoods (●) and hardwoods (O) are shown as C density equivalents.

Soil carbon pool

As forest stands grow, decay or are destroyed by disturbances, CBM-CFS2 transfers litter and coarse woody debris from the biomass pool to one of three soil pools. These materials are then allowed to decay using appropriate decomposition constants, releasing much of their C as CO_2, and transferring the residues to a fourth "slow decay" pool (Kurz and Apps 1994).

For the simulations, the C content of the slow soil C pool for each age class of each stand-type was initialised using CBM-CFS2, beginning with the average soil C density reported above, and assuming a 50-year disturbance interval. When a smooth negative exponential age-class structure (Van Wagner 1978) had been obtained (and the total soil C pool equilibrated), the soil C densities obtained for each simulated age class were then applied to the same stand types in the 1958 age-class structure.

Harvesting

Data on current and projected annual harvesting rates, and on the wood consumed annually by company mills, were estimated from the management plan (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, and the balance from hardwoods. Weldwood believes this rate of harvesting to be sustainable indefinitely, assuming that current silvicultural practices are maintained, that environmental conditions do not change appreciably, and that timber losses due to fire and insect pests do not increase from their current low incidence.

Operational harvesting is subject to certain constraints which needed to be considered by CBM-CFS2. Firstly, operable stands must carry a minimum of 47.5 $m^3\ ha^{-1}$ of merchantable conifer timber. Secondly, the annual harvest is determined by the need for a sustained supply of 2 million $m^3\ yr^{-1}$; hence the area harvested and regenerated annually may vary. Thirdly, current harvesting is concentrated on stands which are usually overmature, with highest volume areas harvested first (although it will shift to younger stands harvested closer to economic rotation age as the supply of older timber is exhausted). The latter strategy is, however, subject to access constraints, which means that some lower volume stands may be harvested each year. Fourthly, for reasons discussed above, the production from many sites is expected to increase significantly due to silvicultural treatments following harvesting of the older age classes.

Of these four constraints, the first two were easily simulated by CBM-CFS2. The third was less easy because the second constraint required the model to harvest the highest volume (or biomass) stands first, but since the model lacks explicit spatial representation, it was not possible to substitute lower volume stands on the basis of accessibility. This problem was overcome to some extent by arbitrarily limiting the annual harvest from the highest volume stands to 20% of the total. The fourth constraint required a slight modification to CBM-CFS2 to track changes in the areas allocated to each stand-type, as older age classes were harvested and then "converted" to higher productivity sites.

Wood processing

All hardwood material is exported to an oriented strand board (OSB) plant, where the bark is used as an energy source for processing. Conifer roundwood is used for producing lumber and bleached kraft pulp. Sawn timber production is approximately 470 000 $m^3\ yr^{-1}$, while pulp production currently averages about 0.385 $Tg\ yr^{-1}$ (air-dry) requiring approximately 5 m^3 of raw material per Mg for a total annual consumption of 1.925 million $m^3\ yr^{-1}$. The kraft pulpmill accepts both roundwood and sawmill residues, of which over 60% originates from within the FMA area, the balance coming from other suppliers. From these statistics, annual balance sheets were constructed showing the amount of forest biomass C transferred to the soil pool during harvesting (Table 23.1), and the amounts harvested within the FMA area entering the forest products C pool (classified as pulp products, construction lumber and bioenergy), or dumped as waste, or lost to the atmosphere (Table 23.2).

Using data on the energy contents of various fuels (Hall and Scurlock 1993) and of wood (Bonnor 1985), the energy equivalents of each component of the balance sheet were estimated. Approximately 74% of mill energy requirements are derived from pulp by-products (hogfuel and black liquor), releasing 0.032 Tg C yr^{-1} from locally produced wood for 1.28 PJ yr^{-1} energy. Other energy needs are met from natural gas (25%) and diesel fuel (1%), yielding approximately 0.45 PJ yr^{-1}, which would release an additional 6200 Mg C yr^{-1} assuming comparable conversion efficiencies. Fossil fuel consumed in forestry operations (vehicles, harvesting equipment, etc.) is not included here.

Forest product decay

Forest product decay functions developed for the national-scale CBM-CFS2 forest product sector sub-model (Kurz et al. 1992), were used to estimate releases of C from different forest products as they decay in buildings and landfills, or are burned as waste or for energy. These decay functions were applied to Weldwood's products, assuming that for any particular type of product manufactured within Canada, the geographic origin does not have any significant impact on its average lifespan. In addition, the Weldwood mills produce a certain amount of waste material, the quantity of which needed to be known in order to close the C balance presented in Table 23.2. To do this, it was estimated that 0.38 Mg C is released as CO_2 from the raw material for every Mg of pulp product, following data from the Canadian Pulp and Paper Association (1991, cited in Wellisch 1992). It was further assumed that the C content of wood is 50% of oven-dry weight. Air-dry bleached kraft pulp was assumed to contain 10% moisture, and a solid fraction of pure cellulose with 45% C, while the solid component of black liquor was assumed to be pure lignin containing 70% C (Salisbury and Ross 1978; K. Hunt, Pulp and Paper Research Institute of Canada, Vancouver, 1994, pers. comm.). These values led to an estimate of 66% for the average C content of the mill waste dumped in the landfill, when calculated as the ratio of residual C to residual wood product mass.

Table 23.1. Balance sheet showing estimated contributions of annual Foothills Forest harvest to soils and net transfers of roundwood to mills, in terms of wood volume, biomass, C content and energy equivalents. (o.d. indicates oven-dry mass.)

	NET TRANSFERS TO ROUNDWOOD AND SOIL				
RAW MATERIALS CATEGORIES	(10^3 m^3)	(Gg o.d.)	(Gg C)	(% C)	(PJ)
Net roundwood extracted					
Conifer (to stud- and pulp- mills)	1843	718	359.0	79.2	14.36
Hardwood (to OSB plant)	97	39	19.5	4.3	0.78
Total net roundwood extracted (to mills)	1940	757	378.5	83.5	15.14
Harvesting residues left on-site					
Stumps, tops, broken stems	60	23	11.5	2.6	0.47
Foliage and branches	N/A	126	63.0	13.9	2.04
Total residues (transferred to soil C pool)[a]	60	149	74.5	16.5	2.51
Total harvest, including losses	2000	906	453.0	100.0	18.12

a Volume of residues is from merchantable timber only, but dry mass includes foliage and branches.

Table 23.2. Balance sheet showing estimated contributions of annual net Foothills Forest roundwood harvest extracted in Table 23.1, to forest products, by-products and landfills, in terms of biomass, C contents and energy equivalents. (o.d. indicates oven-dry mass.)

	END PRODUCTS			
END PRODUCT CATEGORIES	(Gg o.d.)	(Gg C)	(% C)	(PJ)
Construction lumber				
Oriented strand board (OSB)	33.1	16.6	4.4	0.66
Dimension lumber	174.6	87.3	23.1	3.49
Total construction lumber	207.7	103.9	27.5	4.15
Pulp				
Kraft pulp produced from local chips	229.3[a]	114.7	30.3	4.59
Bioenergy				
Bark waste from OSB production (used in process at OSB plant)	5.8	2.9	0.8	0.12
By-products from local chips (used at mill)	59.5	29.2	7.7	1.17
Total bioenergy	65.4	32.1	8.5	1.28
CO_2 emissions from pulpmill and OSB plant (excludes fuel emissions)	153.5	61.4	16.2	–
Pulpmill wastes (transferred to landfill)	100.9	66.4	17.5	2.66
Total consumption/production	756.8	378.4	100.0	12.68

a Converted from air-dry mass assuming 10% moisture content.

RESULTS

Figure 23.3a shows estimated changes in C stored in forest biomass, soils, and the total of these, for the Foothills Forest FMA area since 1958, for Experiment I (no human intervention). Only natural disturbances with an average return interval of 50 years are assumed. It can be seen that the C stored in forest biomass decreases steadily during the first 100 years, as the older stands are lost to wildfires and the sites regenerate naturally, after which it stabilises at about 20 Tg C. Soil C shows a slight increase and then slowly decreases to a stable 110 Tg. Projected total ecosystem storage therefore decreases quite significantly over current-day values before stabilising at about 130 Tg C. These results are explainable by the initial age-class structure (Figure 23.1) which does not follow a smooth negative exponential, and which developed during a period of reduced disturbances. Similar results are reported by Kurz et al. (1994) and Kurz and Apps (Chapter 14), who suggest that reduced disturbances in the early part of the 20th century have contributed, until recently, to a net C sink in the Canadian boreal forest.

The consequences of management, including complete disturbance suppression, and sustained harvesting at 2 million m^3 yr^{-1} were investigated in Experiment III, shown in Figure 23.3c. No change in stand productivity following harvesting is assumed (i.e., regenerated stands follow the same biomass/age curve as the harvested stands they replace). Soil C increases to a stable 160 Tg C, after 170 years (i.e., almost 50% greater than in the unmanaged scenario) while biomass C remains at 50–60 Tg C for about 100 years before decreasing, as harvesting shifts from old-growth to younger stands. Total ecosystem C increases to a maximum of about 220 Tg C by about 130 years, before decreasing with the reduction in biomass C, though it appears to be stabilising around 200 Tg C at 230 years.

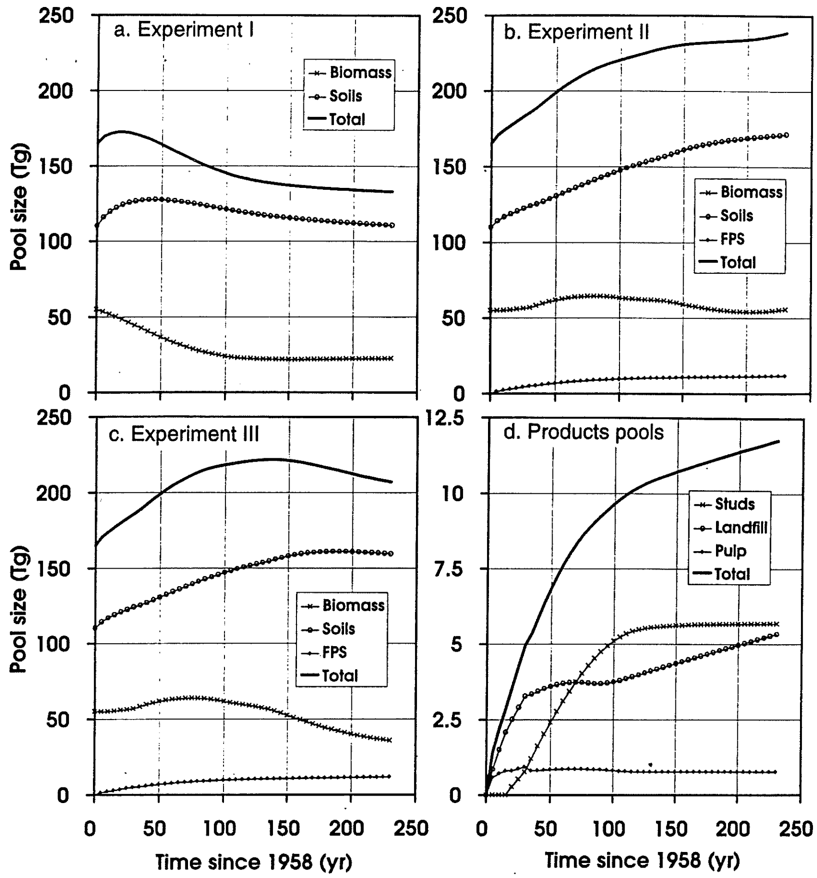

Figure 23.3. 230-year projections of C budget for Foothills Forest for three different management/harvesting scenarios. (a) no management or harvesting, but with natural disturbances occurring at an average return interval of 50 years (estimated from the 1958 age-class structure derived from Figure 23.1). (b) intensive management and sustained yield harvesting, assuming that productivity of lodgepole pine stands increases following harvesting, based on the results of volume yield studies. No natural disturbances assumed to occur since 1958. (c) as (b), but no changes in site productivity following harvesting are assumed. (d) forest products C pool broken down by product categories, for the scenarios simulated in (b) and (c).

Over the same period, Experiment II (Figure 23.3b) shows the additional effect of silviculture, if expected improvements in merchantable volume production are achieved, and if the volume-to-biomass ratios established for fire-origin stands of lodgepole pine are not seriously altered for stands regenerated following harvesting. Silviculture mainly avoids the decline in biomass C after the older age classes are removed, and increases transfers to the soil because of greater stand productivity. This result indicates that planned harvesting rates can be sustained if anticipated improvements in merchantable volume productivity are realised, and will even allow an increase in total C storage compared to the "no silviculture" management scenario

(Experiment III). Consequently, total ecosystem C storage continues to increase throughout the simulation, exceeding values in Figure 23.3c at about 100 years, and appearing to stabilise at about 240 Tg C after 200 years, compared to 135 Tg C for the unmanaged scenario (Experiment I), and 210 Tg C when only fire suppression and harvesting were simulated (Experiment III).

In both managed scenarios, storage of C in soils increases steadily, ultimately reaching significantly higher levels than in the unmanaged scenario, because suppression of wildfire reduces transfers of soil C to the atmosphere, and allows greater transfers from biomass in litterfall. It must be emphasised however, that soil C storage is very sensitive to the assumed decomposition rate. This implies that the estimates of future ecosystem C storage are to be treated with caution, and that the actual soil C storage could be very sensitive to future changes in climate. Nevertheless, these caveats must apply to all scenarios, indicating that within about 100 years, management will likely result in significantly greater ecosystem C storage.

Role of forest products

Figure 23.3d expands the vertical scale of Figures 23.3a–c, in order to examine more closely the long term trends in C storage within the products pool. Note that the harvesting data for Figures 23.3b and 23.3c are identical, since CBM-CFS2 harvests the required timber volume in both Experiments II and III, and differences in tree size are not considered. Initially, pulp and landfills contribute most of total products storage, because lumber production did not start immediately in 1958, and because a high proportion of annual pulp production is immediately transferred to landfills. After production of construction lumber begins, however, its contribution to total product C storage increases rapidly, stabilising at about 5.5 Tg C after 130 years (maximum harvesting rate begins only 30 years into the simulation, and 95% of products are assumed to decay within 100 years). From then on, the C stored in lumber products remains constant, as annual inputs balance losses (25-year half-life). By comparison, pulp products have a much shorter average lifespan, causing production to balance annual losses and hence achieve an approximately steady level under 1 Tg C within 30 years of the start of harvesting.

Role of landfills

The rate of C storage in landfills is directly proportional to the value selected for the recalcitrant fraction. Construction lumber initially contributes only 20% of total products C (when landfill contents are included). After 130 years, however, C storage in lumber products contributes six times the storage in pulp products, even though only 40% of harvested roundwood volume is used in their manufacture (Table 23.2). This apparent benefit of long-lived products is, however, small compared to the steady accumulation of C in landfills. Since 90% of previously manufactured pulp products (and all residues not used for bioenergy) are ultimately discarded in landfills, where it is assumed that 20% will persist indefinitely, there is a rapid accumulation of undecayed pulp material, which contributes significantly to long-term products C storage. Even if the assumption of zero decomposition for this 20% were replaced by one of very slow turnover rates (i.e., thousands of years), the inferences made for the time-horizon of this study would not be substantially affected.

DISCUSSION

Can forest management increase carbon storage?

The results of the simulations reported above indicate that harvesting combined with silviculture are very probably beneficial for long term C sequestration in the specific case of the boreal forest ecosystem considered here. In common with earlier studies (e.g., Chapter 21; Vitousek 1991; Harmon et al. 1990), these results demonstrate that management does affect forest sector C pools, although there are important differences. In general, a matrix of managed stands will store much less total C than the old-growth forest they replace, because the natural disturbance interval governing the average age of the old growth is typically much longer than the economic age of rotation. This is particularly true of the coastal forests of the Pacific north-west considered by Harmon et al. (1990) which exhibit typical natural lifespans of 200 years or more, but which have been replaced by forests managed on a 70–80 year rotation. In our study of a boreal ecosystem, the natural disturbance interval (50 years), is significantly shorter than the typical harvest age (80 years). Hence, management practices aimed at suppressing natural disturbances would also increase C storage.

Secondly, projected increases in lodgepole pine volume production following harvesting are assumed to result in proportionately greater rates of C uptake than would occur in natural (fire-origin) stands of the same age (compare Figures 23.3b and 23.3c). If this hypothesis is correct, then anticipated increases in stand productivity due to silviculture following harvesting will contribute to extra C storage in the lodgepole pine ecosystem.

Contribution of land-filled residues to ecosystem total C storage

At 30 years, total storage in products is about 5 Tg C or 2.6% of the ecosystem total of 190 Tg C. This value is consistent with proportions reported in Matthews et al. (Chapter 24) for global forests (1.3%) and UK forests (1.8%), considering that the Foothills FMA area is managed primarily for wood production and that current availability of large size trees is very high.

The assumption that 20% of wood products discarded in landfills will never decay has a strong cumulative effect on total C storage in the products pool. Anecdotal evidence derived from excavations of old landfill sites suggests that very long decay times are realistic. Not only are anaerobic conditions common in many landfills, but also the by-products of the kraft pulp process may be particularly recalcitrant. Figure 23.3c indicates that if 20% or more of the input material does persist for centuries, its contribution to total ecosystem C storage is also strongly dependent on its C content. The C content was estimated only as a residual term to close the C and mass balances of Table 23.2; hence the true value is currently unknown. Since mass conservation must apply, correct allocation of C among the various end-products could have a significant impact on the contribution of the landfill term. Analysis of land-filled residues would help resolve this problem.

If the assumptions used in the simulations are valid, by the end of the 230-year simulation period, pulp products, and wood products in landfills, would contribute 50% of total products C storage, totalling 12 Tg C, or approximately 5% of total ecosystem C.

Other factors affecting future forest C budgets

The projected long-term increases in C storage due to management and harvesting are based on several assumptions: (1) environmental conditions will not change in the future; (2) complete suppression of natural disturbances (fires and pathogen attacks) can be achieved; (3) projected increases in aboveground productivity resulting from silvicultural treatments are realistic and sustainable; (4) below-ground C dynamics (i.e., fine root turnover) are not significantly changed by management practices; (5) these protection and management procedures require no major increases in fossil energy consumption.

Changes in climatic conditions are expected to lead to changes in forest productivity, as well as in disturbance frequency, resulting from direct effects on growth physiology, seed production and germination success, and indirect effects on the population behaviour of endemic insect pests and disease organisms (e.g., see Chapter 7; Flannigan and Van Wagner 1991; Kurz and Apps 1994; Sirois 1992; Bergeron and Flannigan 1995; Fleming and Volney 1995). Such changes would generally influence the C dynamics of both managed and unmanaged ecosystems, and most likely in the same direction, but detailed analysis of the differential effects are beyond the scope of this paper. Briefly, even if the simulated absolute gains in C storage resulting from management cannot be achieved in reality, it seems plausible that a net increase will occur relative to the natural ecosystem in the area of this case study, assuming identical changes in climate. Conversely, it is difficult to conceive of a situation where the managed ecosystem would lose more C than the unmanaged under a warming climate, when management objectives are aimed at maximising wood production, because the unmanaged/unprotected/unharvested forest is likely to incur more widespread losses from disturbances.

Offsetting fossil energy C emissions

Approximately 7% of harvested roundwood is used for energy (Table 23.2), which represents a net reduction in fossil energy releases of approximately 0.018 Tg C yr^{-1} during processing if compared to a mill entirely dependent upon fossil energy. The total energy content of mill products is approximately 12.7 PJ yr^{-1}, of which approximately 2.7 PJ yr^{-1} is in pulp wastes. After subtracting the 0.45 PJ yr^{-1} currently obtained from fossil sources and 1.3 PJ yr^{-1} derived from bioenergy (Table 23.2), the managed forest could be viewed as a net producer of about 11 PJ yr^{-1}, which if fully utilised would correspond to a reduction in annual fossil C emissions of 0.15 Tg (natural gas) to 0.31 Tg (coal).

A refined analysis should account for all fossil fuel consumed in forest management and harvesting operations. It is expected, however, that the consequent emissions have little impact on the overall net C balance within the FMA area. More importantly, such an accounting should be balanced against the reduced GHG emissions obtained by substituting wood products for equivalents requiring much greater energy inputs to manufacture (e.g., galvanised steel studs). A complete C budget should therefore include the C cost of providing alternatives to wood products to consumers (see also Chapters 18 and 24).

Global implications

At the global scale, the time taken to saturate the forest products pool may be long indeed, because as the CBM-CFS2 simulations show very clearly, it will depend very significantly on the long-term fates of some products. If we accept the assumption that 20% of material deposited in landfills persists indefinitely, and that long-term management of landfills does not alter (e.g., due to changes in waste management policies), then the landfill contribution could significantly increase the effective long-term C storage attributable to global forest products.

In reality, the global products pool is unlikely ever to be fully saturated. Not all forests are exploited commercially, while for many of those which are, sustained yield management objectives are lacking. Furthermore, for some regions, there are inaccurate records of past and current production, and it is likely that current practices will change dramatically in the future as commercial demands and public expectations change. Such considerations will inevitably make estimating the maximum size of the global products sink a difficult proposition, but it may yet be possible to derive a conservative value for its upper limit. Carbon budget analyses similar to the one presented here could be carried out for representative forest management units in other regions of the world. Where maximum sustained yield harvesting is both a stated objective and demonstrably achievable, it should be possible to make estimates of regional saturation times (following first entry to the forest resource) and given estimates of sustained yield forest areas, the approximate magnitudes of the regional products sinks. The total of these regional estimates could then be used in global C accounting as a known offset for current and future GHG emissions.

The magnitude of the global products sink is vulnerable to the possible impacts of climate change. It will therefore be necessary to consider projections of near-future forest vegetation dynamics and potential harvesting yields under global change scenarios, as inputs to any assessment of the size of the long-term products sink. For boreal and temperate forests at least, it is probable that there will be a period of increased ecosystem disturbances during which large amounts of biomass (and soil) C will be released, with less raw material consequently being available for harvesting. There are two major directions forest management can take to help counteract this impact: firstly, increased emphasis on protection from fires and insect attacks (see also Chapters 7 and 8); and secondly development of large-scale facilities for handling wood salvaged from disturbed areas.

CONCLUSIONS

Estimates were made of the past and future contributions of forest ecosystem compartments, including forest products, to total C sequestration in a Canadian boreal forest management unit. Given that the management objective of maximum sustained yield is achievable, the products pool may be viewed as a sink for atmospheric C. The finite size and duration of this sink are dependent upon assumptions made concerning the efficacy of forest management in increasing and maintaining forest productivity, and the longevity of harvested products, particularly those discarded in landfills.

In this specific case study, replacing natural disturbances (with a return interval of about 50 years) by sustained yield harvesting (practised on an approximate 80-year rotation), would result in significant increases in total C storage, perhaps exceeding 50% within 150 years, compared to the unmanaged forest, particularly if silvicultural treatments can succeed in maintaining elevated productivity. If the assumptions made here are correct, then for the managed forest ecosystem, the present-day storage in forest products is about 2.5% of total ecosystem C, potentially increasing to 5% over the next 200 years.

The analysis presented here could be applied to other regions of the world. Relationships established among standing forest biomass, soil C storage, sustained yield harvests, and product utilisation, would be used to determine effective upper limits to the regional products sinks, and their approximate saturation times. From such estimates, and information on the forest areas under sustained yield management within each region, it should be possible to make a realistic assessment of the current and potential future roles of the global forest products pool as a sink for atmospheric CO_2.

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