Atmospheric Carbon and Pacific Northwest Forests

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Introduction

Predictions of the effects of increased carbon dioxide (CO_2) concentration in the global atmosphere (Houghton *et al.* 1990) are leading to growing concerns about environmental change. The concentration of CO_2 in the atmosphere has increased by 26% from the pre-industrial level of 280 to 353 ppm in 1990 (Watson *et al.* 1990). The CO_2 increase is attributable to the ubiquitous burning of fossil fuels, which release carbon (C) to the atmosphere, and to changes of landuse which replace vegetation of high C density, such as forests, with urban or agricultural vegetation. Fossil fuel burning annually releases 5-6 giga tonnes (Gt) C (Watson *et al.* 1990) to the atmosphere -- an amount equivalent to the C contained in the forest biomass of the entire Canadian Pacific Northwest (PNW) forest (Kurz *et al.*, in prep.).

Forests play an integral role in the global C cycle. Through photosynthesis, CO_2 is taken up from the atmosphere and stored in plant biomass, which will eventually die and decompose or burn, returning the CO_2 to the atmosphere. Globally, forest biomass contains about two-thirds of the amount of C currently contained in the atmosphere, while detritus and soil organic C pools contain about twice the amount of atmospheric C (Watson *et al.* 1990). Approximately 10-15% of atmospheric C is exchanged annually with terrestrial ecosystems. Anthropogenic changes to forest ecosystems are therefore potentially important to the functioning of the global C cycle.

This paper will address the role of PNW forest ecosystems in the C cycle and discuss the effects of forest land management decisions on the exchange of C between forest ecosystems and the atmosphere. Specifically, the question of how forest land management decisions affect the future C budget of the region will be addressed. First, the key components of forest-atmosphere C exchange and the implications of anthropogenic actions to this C exchange will be discussed.

A conceptual model of the role of forest ecosystems in the C cycle will be presented in the next section. Section three will briefly describe the quantitative results of a C budget model of forest and forest sector activities in the Canadian PNW forests. Section four will outline issues that may be considered by forest land managers concerned about the effects of their management decisions on the C cycle. The paper will conclude with a short discussion of the effects of a changing climate on the C cycle. While it is recognized that there are many functions and values of forest ecosystems, this paper will focus on the contribution of forest ecosystems to the C cycle.

Conceptual Model

C pools and C transfers

There has been much discussion and some confusion about the role of forests in the global C cycle. To facilitate the discussion in the remainder of this paper, we want to briefly outline some basic principles and address some common misconceptions.

The purpose of developing a C budget is to estimate the uptake and release of C from forest ecosystems, and the C release from forest products, which have been derived from those forest ecosystems. For the purpose of calculating budgets, we quantify several C pools, transfers between those pools, and fluxes of C between the ecosystem and the atmosphere. Within forest ecosystems, C is contained in both the biomass and the soil. The biomass C pool comprises living trees, shrubs, mosses, and other vegetation. In our nomenclature, the soil C pool contains all dead organic matter including soil organic C, above and below ground plant detritus, coarse woody debris, and standing dead timber.

Carbon is taken up exclusively through photosynthesis by the living biomass. All C, which is transferred to the soil C pool, was previously removed from the atmosphere through photosynthesis. Transfer of C to the soil pool occurs through litterfall, mortality of fine and coarse roots, and the death of trees. In our model, we distinguish two types of C transfer to the soil C pools: a continuous transfer (litterfall, mortality of individual trees) and an event-specific transfer associated with disturbances such as fire and windthrow.

In our conceptual model, harvested material leaving the forest ecosystem enters a new C pool consisting of forest products in various forms, including the material contained in landfills. Most construction lumber retains C in buildings for many decades. Some forest products, such as pulp and paper, may appear short-lived, but unless they are burned they may retain much of their C while stored in landfills. Manufacture of forest products generates waste and by-products, many of which are burned for energy production or for waste reduction, thereby releasing CO_2 to the atmosphere.

C dynamics

Dynamics of the biomass and soil C pools are determined by forest growth, transfer of C from biomass to soil pools, and C release through decomposition. Figure 1 shows a schematic diagram of C dynamics in the biomass and soil C pools following a generic disturbance. We distinguish three phases of C dynamics following a disturbance. In the first phase, the release of C from decomposing material is typically greater than the uptake of C in the regrowing vegetation. After some years, in the second phase, biomass and soil C dynamics result in a net C uptake by the ecosystem. In the third phase, the biomass C pool may tend towards some ecosystem-specific maximum value or may even slowly decline as the stand breaks up. In either case, C is continually transferred to the soil C pool through tree mortality and litterfall. Thus, depending on the net balance between biomass and soil C pool changes, total ecosystem C can continue to increase despite a steady state or declining biomass C pool. Net ecosystem production (NEP) (Waring and Schlesinger 1985) and not current annual increment (CAI) is thus the appropriate measure of ecosystem C sequestration rates. The duration of each of these

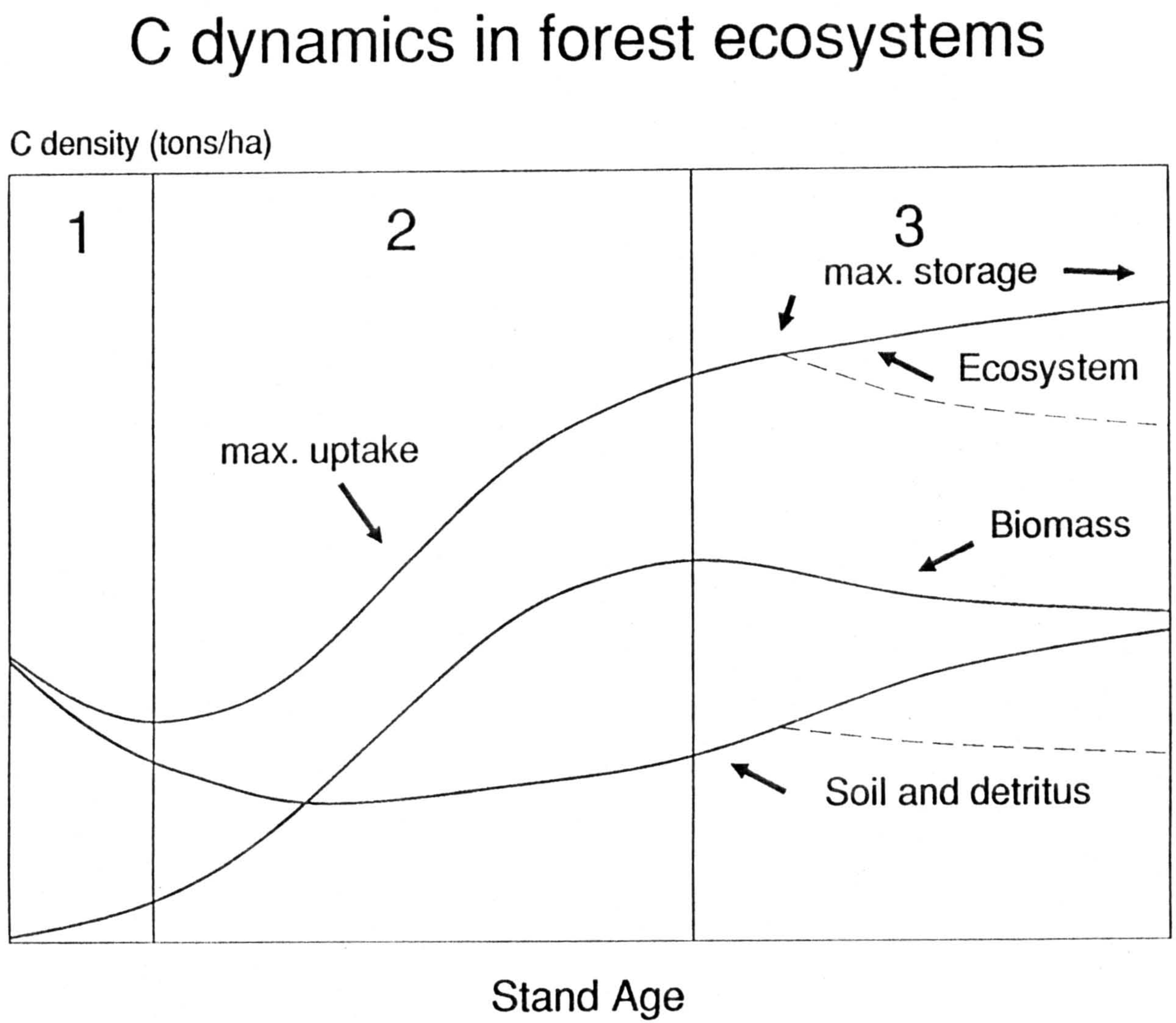

Figure 1: Generalized dynamics of biomass, soil, and total ecosystem C in forest ecosystems.

phases differs among ecosystem types, as does the size of the soil and biomass C pools. Figure 1 also shows that maximum C uptake and maximum C storage do not occur during the same phase of ecosystem dynamics.

One common misconception is that old-growth forest ecosystems (i.e., stands in phase 3 of Figure 1) are not taking up C because the current annual increment (CAI) of timber volume is zero or even negative. Much of the C uptake of such stands, however, is transferred to the soil C pools, as expressed in the high rates of litterfall and coarse woody debris input typically observed in such ecosystems (Harmon and Chen Hua 1991, Harmon *et al.* 1986). The ecosystem may thus still be a net C sink (i.e., NEP may still be positive).

Disturbances

In addition to the continuous processes resulting from stand dynamics, disturbances periodically affect forest ecosystems and alter the initial size and the subsequent dynamics of C pools, and the age-class structure of forests. Event-specific disturbances include fire, insect-induced stand mortality, windthrow, and harvesting. All disturbances transfer C between pools and, in cases such as fire, also release C directly to the atmosphere. Such disturbances, however, even severe wildfires, release only a proportion of C from biomass and soils to the atmosphere. Another portion of biomass C (e.g., dead standing and downed trees) is transferred to the soil C pool and will decompose during future decades or centuries. This transfer is ignored in many C budgets, which often account only for C fluxes between ecosystem and atmosphere and not for the transfers within ecosystems. We will show later in this paper that it is important to understand both the quantities of C and the type of biomass material involved in this C transfer within ecosystems.

The frequency and extent of disturbances in a forest region has a major influence on the age-class distribution of forest stands. Disturbances may occur at any time during stand development. Forests of different ages contain different amounts of C in the biomass and soil pools and have different rates of C exchange with the atmosphere. The age-class distribution of a forest region is therefore a major determinant of both the amount of C stored and the rate of C uptake (Figure 1).

The natural disturbance regimes (not including logging operations) are the manifestation of the combined effects of regional climate, the presence and dynamics of insect populations, extreme weather events, and the state of forest health. In the Canadian Pacific Northwest, fire has historically been the primary cause of disturbance in forest ecosystems. This is still the case in National Parks, where the current forest age-class structure reflects natural disturbance regimes.

Fire cycles in the PNW differ greatly in wetter coastal and drier interior regions, being mainly attributable to differences in precipitation and evapotranspiration. In coastal regions, fire cycles have historically been several centuries long, thus allowing individual stands to achieve ages of over 1000 years (Schmidt 1970). In the interior regions, fire cycles are significantly shorter, typically in the range of 50 to 150 years (Johnson *et al.* 1990, Johnson and Larsen 1991). These differences in fire cycles are the major reason for the differences in C storage in coastal and interior ecosystems in the PNW.

The Current C Budget

To improve our understanding of the current role of Canadian forests and forest sector activities in the global C cycle, a detailed C budget model has been developed. This model provides an estimate of the exchange of C between the forests and the atmosphere for the reference year

1986. Details of the model structure, the data sources and the assumptions are described elsewhere (Kurz *et al.*, 1991; Kurz *et al.* in prep.; Apps and Kurz, 1991).

It must be emphasized that the results obtained to date apply only to a single year. The results must not be extrapolated into the past or the future without considerable caution. Two reasons for caution are the high between-year variation in disturbance regimes and the shifts in forest age-class structure resulting from changes in disturbance regimes, both of which could significantly affect the C budget.

In the C budget model, Canada is partitioned into 11 ecoclimatic provinces (EPs) (Ecoregions Working Group 1989). Four of these regions comprise the Canadian portion of the PNW: the Pacific Cordilleran (PCor), the Interior Cordilleran (ICor), the Cordilleran (Cor), and the Subarctic Cordilleran (SCor). The C budget model integrates the C dynamics of the biomass and soil C pools, the C release and transfer resulting from disturbances, and the release of C from forest products harvested in these EPs in the past 40 years.

In the 4 EPs of Canada's PNW, approximately 0.48% of the forest area is disturbed annually (Table I). Natural disturbances have high between-year variability, and the statistics summarized here include logging statistics for 1986, fire statistics (average 1980-1989), and insect statistics (average 1977-1981). These disturbances are not distributed evenly through the four ecoclimatic provinces: in the Subarctic Cordilleran, only 0.07% of the forest area is disturbed annually compared to 0.65% in the Interior Cordilleran (Table I). The contribution of different disturbance regimes also differs among EPs. In the Cordilleran EP, natural disturbances affect 0.26% of the forest area, while logging disturbs 0.2%. In the Pacific Cordilleran, natural disturbances affect only 0.02% of the forest area annually, compared to 0.44% from logging.

Figure 2 provides an overview of the C budget of Canada's PNW forests for the year 1986. Forests and forest sector activities in the four ecoclimatic provinces resulted in a net sink of 16 mega tonnes (Mt) C. Disturbances resulted in a 14 Mt C net reduction of the biomass C pool, through transfer of C to the forest products sector (21 Mt C), the soil C pool (14 Mt C), and the atmosphere (4 Mt C). The 8 Mt C net litterfall input to soil C pools (which contain all dead organic matter, except peat) is calculated as the difference between detritus inputs and decomposition releases. In addition, disturbances transfer 14 Mt C from biomass to soil C pools. The net increase in the soil C pools (19 Mt C) is greater than the net loss from biomass pools (14 Mt C), such that total ecosystem C increases by 5 Mt C. The transfer of biomass to the forest products sector (20.7 Mt C) results in a net increase of 11.2 Mt C in the forest products pool after accounting for the C losses to the atmosphere from oxidation of forest products harvested during the previous 40 years.

Our results demonstrate the importance of the forest products C pool in the C cycle, since it accounts for over two-thirds of the net increase of the C storage in Canada's PNW forests and in forest products derived from this region. It should be noted, however, that the analysis neither accounts for the use of fossil energy in forest management or production processes, nor does it account for the bioenergy generated from burning of biomass.

We must once again caution against extrapolation of this result for a single year into the future or the past. Work is in progress to model changes in dynamics of C budgets in space and time. We must also emphasize that although these results are derived from the first comprehensive C budget of the Canadian forest sector, considerable uncertainties remain (Kurz *et al.* in prep.).

Table I: Summary of forest area in the National Biomass Inventory, percent of area disturbed (total and 5 disturbance types), and the disturbance cycle for each of four ecoclimatic provinces and the total for Canada's part of PNW forests.

Ecoclimatic Province	SCor[a]	Cord	ICor	PCor	PNW SUM
Forest Area (10^6 ha)[b]	4.3	61.3	15.3	10.6	91.5
Area disturbed (% yr^{-1})	0.07	0.47	0.65	0.46	0.48
Wildfire	0.07	0.24	0.05	0.02	0.18
Insects	0.00	0.02	0.09	0.00	0.03
Cut & burn	0.00	0.04	0.10	0.11	0.06
Clear cut	0.00	0.15	0.29	0.31	0.18
Partial cut	0.00	0.01	0.12	0.02	0.03
Disturbance cycle (years)	1424	213	154	219	208

a Ecoclimatic provinces are Subarctic Cordilleran (SCor), Cordilleran (Cor), Interior Cordilleran (ICor), and Pacific Cordilleran (PCor). PNW-Sum is the total for the four ecoclimatic provinces.

b Source: Bonnor 1985

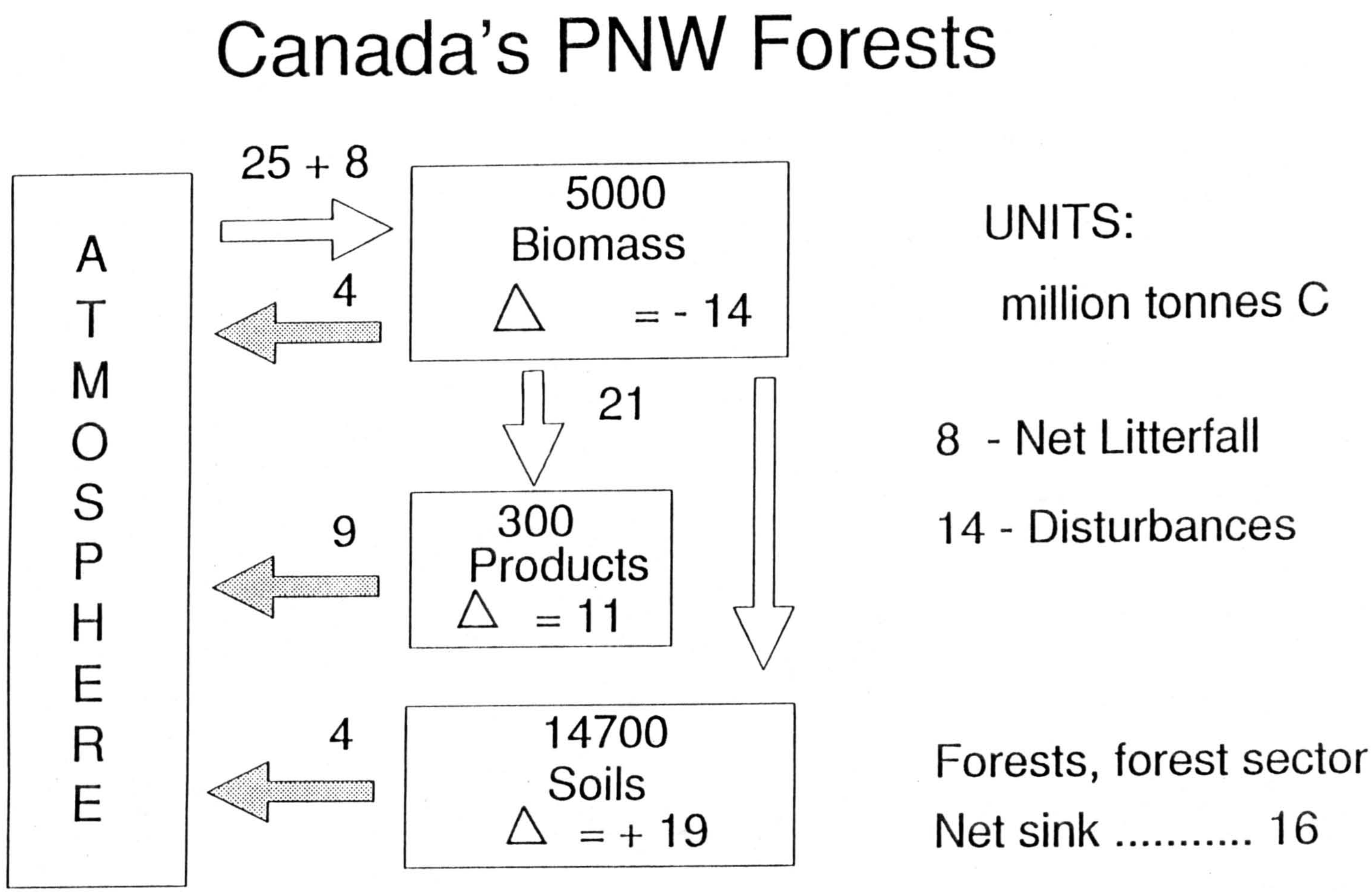

Figure 2: Summary of C pools, net fluxes, and the resulting budget (for 1986) for the forests and forest sector activities of Canada's pacific northwest. Net litterfall is calculated as the difference between total litterfall and C release through decomposition prior to accounting for disturbances. The estimated annual peatland net C uptake of 0.9 Mt C is omitted from this budget.

Considerations for Forest Managers

Human activities influence C storage and C cycling in the forest sector through logging, silvicultural activities, protection against fire and insects, and the utilization and storage of forest products. An assessment of the effects of human influences should be obtained by comparing the C budgets of managed forests with those of forests under natural disturbance regimes. It is important not to view forest management activities in isolation, because storage of C in unmanaged forest stands is a cyclical process of C accumulation followed by C release during and after disturbances, followed again by C accumulation. Leaving forests unharvested, therefore, does not imply that C will be stored indefinitely.

Four aspects need to be considered in this comparison of managed and unmanaged forests: the difference in age-class structure, the C release to the atmosphere at the time of disturbance, the rate of biomass regrowth including the duration of the regeneration delay, and the difference in C storage in the detritus and forest products C pools.

Shifts in age-class structure

The age-class structures of managed and unmanaged forests differ if their disturbance cycles differ. Logging activities will shorten the disturbance cycle unless natural disturbances are simultaneously reduced through fire and pest management to offset the additional disturbance from logging.

In wetter coastal regions, Pacific Northwest old-growth forest ecosystems are large C storage pools because they have been largely undisturbed for centuries. Their conversion to forests managed at a shorter rotation, i.e. a shorter disturbance cycle, will inevitably reduce the C stored in those systems (Cooper 1983, Harmon *et al.* 1990). The off-site C storage in forest products is not significant enough to balance the loss of ecosystem C storage, thus resulting in a net release of C to the atmosphere (Dewar 1990). Harmon *et al.* (1990) estimated that the conversion of 5 million ha of old-growth forest in the United States Pacific Northwest has added between 1.5 and 1.8 Gt of C to the atmosphere.

C transfer during disturbances

C transfer during disturbance differs between logging and natural disturbances. Fires can release a large proportion of ecosystem C to the atmosphere, while windthrow will have little immediate effect on total ecosystem C. Natural disturbances transfer large amounts of biomass C to the soil C pools while logging removes some of this biomass from the ecosystem. Logging itself does not release biomass C to the atmosphere at the time of disturbance, unless slash is burned. Wildfires oxidize foliage, branches, and other small diameter above-ground biomass, whereas logging leaves behind such material while removing more of the larger diameter components. It is readily apparent that these differences in detrital types will affect the post-disturbance dynamics of the soil C pools.

C storage pools can be conserved to the extent possible while maintaining forest management objectives. This conservation does not necessarily imply maintaining existing pools. For example, where low intensity disturbances are required to accelerate the regrowth of the post-disturbance vegetation, it may be appropriate to accept a short-term reduction in C storage pools provided that the subsequent gain in C uptake by the regrowing forest is greater than the C loss. What is required is a careful analysis, over an appropriate planning horizon, of the C consequences (i.e. net release to the atmosphere) of various forest management actions.

For example, what is the C cost per unit timber harvested from logging old-growth forests compared with that of logging a second-growth forest? How does it differ between wetter coastal and drier interior forests? There are forest management objectives other than timber harvest, and these too may require an analysis of the C implications associated with achieving them.

Growth Rates

The rate of biomass regrowth following disturbance depends on the nature and intensity of the disturbance. Short regeneration delays followed by rapid regrowth will shorten the phase of net ecosystem C loss (Phase 1 in Figure 1) and will increase the average C storage during a rotation. For example, a well-executed logging operation that takes advantage of advanced regeneration already at the site will obviously result in more rapid biomass C accumulation than a severe wildfire followed by years of regeneration delay.

Forests in the PNW are characterized by very high growth rates. Proper forest management can maintain and enhance these growth rates, thereby increasing the rate at which C, previously released during disturbances, is removed from the atmosphere. Care must be taken, however, to include a complete C accounting of such silvicultural activities. For example, it has been suggested (Sedjo 1989) that N fertilization can be used to increase forest productivity and the rate of C sequestration. Note, however, that the production, transportation, and distribution of N fertilizers consumes fossil energy, which will result in CO_2 releases to the atmosphere. From the perspective of C budgets, N-fertilization is only beneficial if the net increase in forest ecosystem productivity offsets prior fossil CO_2 releases.

Soil and forest products C dynamics

During disturbances, biomass C is transferred to the soil (including detritus) and forest products C pools. Through oxidation, C will subsequently be released from both pools. The soil and forest products pools differ from the biomass pool in that direct uptake of atmospheric CO_2 is not possible. We must compare the C dynamics and storage in soil and forest products of the managed system with the C storage in soil of the unmanaged forest ecosystem. If the rate of C release from forest products and soil in the managed system is slower than the release from the soil pool in the unmanaged system, then C retention in the managed system is invariably greater than in the unmanaged system (assuming similar biomass C dynamics).

Although logging operations represent an export of ecosystem C, they also initiate C accumulation in a new pool. Harvested biomass enters the forest products sector where it is converted to wood products with different use and C retention characteristics. Assessment of C storage and dynamics of the forest products C pool requires tracking the fate of harvested biomass through a series of production processes, the life of the end product (including possible recycling), and final disposal.

Long-lived forest products can contribute to off-site C storage. By increasing the duration for which C is retained in forest products, the size of the forest products C pool is increased, effectively reducing C emissions to the atmosphere. It should be noted that analysis of the forest products sector C budget should also consider the use of fossil energy in the production processes. Recycling of paper products, for example, is one popular conservation option. The fossil energy consumption in paper collection and reprocessing must, however, be included when assessing the net effect of this policy decision on the global C cycle.

Energy and product substitution

We must re-emphasize that the release of fossil C to the atmosphere is the primary reason for concern because there is no practical means by which C can be returned to the fossil C pools. To put fossil energy C release in perspective, consider that the annual global emission of fossil C (5 - 6 Gt C yr^{-1}, Watson *et al.* 1990) is equal to 42 - 50% of the 12 Gt C (Apps and Kurz, 1991) stored in the above-ground biomass of the entire Canadian forest. In contrast to fossil C pools, the growth of biomass from which forest products are derived removes C from the atmosphere. When forest products substitute for fossil energy sources they reduce the net addition of fossil C to the atmosphere. This can be achieved in one of two ways.

Firstly, bioenergy, the generation of energy from biomass either directly through burning or indirectly after the conversion to organic fuels, may substitute for fossil energy. Provided that total energy consumption does not increase, this substitution will reduce the net emission of fossil C to the atmosphere to some extent. Secondly, forest products can also perform the functions of other materials that are produced using fossil energy sources: for example, the production of aluminum studs for building construction requires large quantities of energy, which is often derived from fossil energy sources.

Climate Change Impacts

The responses of forest ecosystems to climate change will be complex and therefore difficult to predict. The conceptual model outlined in Section 2 provides a framework for the analysis of potential effects of climate change. The primary impacts are likely to be: (1) changes in the growth dynamics of forest biomass; (2) changes in the dynamics of soil C pools; and (3) changes in disturbance regimes, especially fire (Flannigan and van Wagner 1990) and insect attacks.

Research is in progress to modify the C budget model of Canadian forests and forest sector activities to assess the implications of various scenarios of climate change on the C budgets. Particular emphasis will be placed on changes in age-class structure of forest regions, which, as was shown above, is one of the major determinants of C storage and C dynamics. Changes in growth and decomposition rates in response to climate change in ecosystems of various ages or stand developmental stages will need to be predicted prior to integrating C fluxes in space and time.

Conclusions

Forests play an important role in the global C cycle. In the PNW, wetter coastal and drier interior ecosystems can be distinguished by differences in their natural disturbance regimes. The long disturbance cycles of coastal systems have allowed large accumulations of C in biomass and soil pools. Logging in the coastal region has significantly altered the age-class structure of these forests, thus reducing the total amount of C stored in them. The impacts of logging on C storage are less significant in interior regions where the age-class structure generated by natural disturbance regimes is more similar to that of managed forests. Off-site storage of C in forest products pools has the potential to offset the C loss from forest ecosystems. This effect is greatest when long-lived forest products are manufactured from short-lived forests and is minimal when short-lived forest products are generated from long-lived forests. Forest managers should be aware that decisions about harvesting, silviculture, site preparation, and forest products utilization do affect the net exchange of C between the atmosphere and the forest sector. Forest management decisions can thus reduce the rate of atmospheric C increase.

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