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ESTIMATING THE ANNUAL CARBON BUDGET OF THE FOOTHILLS MODEL FOREST

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By

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Estimating the Annual Carbon Budget of the Foothills Model Forest

Introduction

Carbon (C) storage in forest ecosystems is increasingly being viewed as a criterion of sustainable forest management. At the same time environmentalist criticism of Canadian forestry practices often refers to the supposedly negative impacts of harvesting on the environment. Forest C dynamics are also likely to be sensitive to environmental changes, such as climatic warming, particularly in the boreal regions. The net carbon budget of a forested region is therefore increasingly considered as an indicator of "ecosystem health".

The energy sector also increasingly sees forestry as a potential method of mitigating emissions of greenhouse gases from fossil fuels. The scope of forest management is thus rapidly changing: moving from a local needs (timber supply) global ones (mitigation of climate change)

For these reasons, an understanding of the possible effects of alternative forest management approaches on the forest C budget is likely to become increasingly important to managers and policymakers alike.

The Canadian Forest Service's CBM-CFS2 (Carbon Budget Model of the Canadian Forest Sector) provides an integrated assessment tool (Apps and Kurz 1991). It considers the C associated with forest growth, soil processes, ecosystem disturbances (including harvesting) and wood products (Kurz et al.1992, Apps and Kurz 1993, Kurz and Apps 1994). It tracks the transfers of C among all the known C pools, from and to the global atmosphere, to derive an estimate of the net gain or loss of C by a forested area. The structure of the model thereby enables the investigation of effects of changes in management—and environmental factors—on the forest C budget.

The first purpose of this study was to adapt CBM-CFS2 to derive an estimate of the current and past C budgets of the Foothills Model Forest FMA area. The second objective would be to build on the knowledge so gained to examine the future changes that may result from different management and environment scenarios. Thus the analyses was designed to provide information to help local forest managers assess the effects of plausible management strategies on the local forest C budget. This will be of particular value in assessing the effects of possible increases in ecosystem disturbances, such as fires and insect attack, that may be associated with climate change, and of possible management and harvesting interventions to counteract these effects.

The results of 17 sets of simulations using the modified model have now been studied with considerable effort. The results appear to be consistent with our understanding of forest ecosystem processes and our knowledge of recent disturbance histories, both for the Foothills FMA and for boreal ecosystems in general. The model has produced credible C budget assessments for a range of scenarios, which are now available for use as part of a decision support system. This should allow better evaluation of forest C storage as an indicator of sustainable management.

Project Status

Work Completed

A total area of 820,657 ha, representing the forested area of the FMA included in Weldwood's 1988 inventory, was divided into 14 spatial units, corresponding to the intersections of four ecoregions (Montane, Sub-alpine, and Upper and Lower Boreal-Cordilleran) and the five management working circles. After resolving several problems in the inventory database, the 1988 age-class distribution, together with some ancillary information on the history of harvesting and recent fires, was used to reconstruct the age-class distribution in 1953, to represent the state of the FMA before harvesting commenced.

Work was slowed, however, by the discovery of several major inconsistencies in the inventory data, mainly related to the reported ages of stands, compared to independent knowledge of the timing and locations of past fires and harvesting operations (Dan Farr, personal communication). Some of these inconsistencies were due to errors in the inventory and some to errors in our interpretation of the data. Additional difficulties were encountered in dealing with forested areas reported as having age zero. Of these areas, some were unstocked, some were unproductive, and some were too young at the time of the inventory to be properly classified.

The approach adopted to solve this problem of misidentification was to reallocate these areas with the attributes of a median yield curve (YC). The areas of age-zero stands were reallocated separately within each spatial unit, in simple proportion to the areas of existing stands up to age 32 (the oldest regenerated stands in the 1988 inventory).

An initial test of the object-oriented[2] CBM-CFS2 model was to examine how well it simulated age-class dynamics. The model was initialized with the reconstructed 1953 age-class distribution and then ran forward in time to 1988 using the known history of harvesting and fires since 1953. The simulated age-class structure in 1988 was then compared t o the actual age-class distribution in 1988 derived from the inventory data. The comparison was very favourable (see Appendix II, Price et al. 1997, Fig. 1).

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[2] The rewriting of the CBM-CFS2 code in the object oriented language C++ was performed in part with Foothills Forest support in years 1 and 2 of this project and reported in those years

Seventeen 'production' runs of the model have now been completed, each of which generated a large volume of data for each of the 14 spatial units in five-year time steps. The data contained in three key output files which report for each spatial unit in five-year timesteps, the C pool sizes, five-year C fluxes and age-class distributions of average C densities in soils and biomass. These were then combined to generate C budget summaries for each ecoregion, each working circle and for the total FMA area. In total 510 separate summaries were thus compiled (10 summaries per file, 3 files per run and 17 runs) and are reported in Appendix I and Appendix II (See also Price et al. 1997 Table 1).

These summaries report the results of a set of different scenarios of past and future trends in C storage and transfers (from 1953 to 2238). Several runs are sensitivity tests in which the values of single variables were varied to examine their effects on the forest C balance. The variable chosen (natural fire return interval, harvesting intensity and soil decomposition rate) include those that may be possible sources of error in the initial assumptions. Some runs also investigate the interaction of possible future changes in fire frequency with planned rates of harvesting. Assessment of the C flows associated with the management and production side has been delayed, however, pending the receipt of additional information from Weldwood (see discussion below).

Results

A detailed assessment of all the model output is beyond the scope of this report, so only some highlights will be presented here. More in-depth analysis and discussion has been presented in the peer-reviewed paper (Price et al. 1997) recently accepted for publicaiton in the *Canadian Journal of Forest Research* (Appendix II). For direct access to the output data, the reader should examine Appendix I and explore the set of *Excel* spreadsheets on the attached floppy disks.

C Budget 1988

Tables 1 and 2 present some new information not previously reported: "snapshot" analyses of the C budget for the reference year, 1988 (the year of the forest inventory upon which the model simulations were based). Of these, Table 1 is the most precise estimate of the true C balance for the Foothills Forest FMA area that can be obtained with the information presently available.

It is worth noting that during the period 1983–1988, no natural disturbances were reported, so all C fluxes associated with disturbances are set to zero. The table shows that all ecoregions and all working circles within the FMA area were net sinks in the period 1983–1988. The Montane ecoregion was a particularly strong sink, probably because, according to the data base, much of its (very small) extent was disturbed just prior to 1953. Hence it was in a rapidly growing phase in 1988 , accumulating C at a high rate.

Table 1. Carbon budget 'snapshot' of the Foothills Model Forest for 1988 (Mg C yr^{-1}), based on known history of natural disturbances and harvesting.

	By Ecoregion				By Working Circle					
	Montane	Subalpine	U. Boreal–Cordilleran	L. Boreal–Cordilleran	Athabasca	Marlboro	Embaras	McLeod	Berland	FMA Total
Land area (ha)	350	102565	542383	175359	156506	140333	165784	170769	187265	820657
Forest biomass										
Net growth before disturbance	420	58107	484405	167209	156541	116769	138099	137259	161474	710141
Disturbance releases to atmosphere										
Natural (fire)	0	0	0	0	0	0	0	0	0	0
Harvesting	0	0	0	0	0	0	0	0	0	0
Subtotal disturbance releases	0	0	0	0	0	0	0	0	0	0
Disturbance transfers to soil										0
Natural (fire)	0	0	0	0	0	0	0	0	0	0
Harvesting	0	-18143	-93147	-1760	-5875	-25103	-9662	-16852	-55558	-113050
Subtotal disturbance transfer	0	-18143	-93147	-1760	-5875	-25103	-9662	-16852	-55558	-113050
Transfer to forest products	0	-17726	-97481	-1866	-6244	-24882	-10485	-16344	-59118	-117073
Net change	420	22238	293777	163582	144422	66783	117952	104063	46798	480017
Forest soils										
Net detrital inputs before disturbance	219	34144	42033	17289	31914	-8028	18360	12035	39403	93685
Disturbance transfer from biomass	0	18143	93147	1760	5875	25103	9662	16852	55558	113050
Disturbance releases to atmosphere										
Natural (fire)	0	0	0	0	0	0	0	0	0	0
Harvesting	0	0	0	0	0	0	0	0	0	0
Subtotal disturbance releases	0	0	0	0	0	0	0	0	0	0
Net change	219	52287	135179	19050	37789	17076	28022	28888	94962	206735
Forest products										
Transfer from biomass	0	17726	97481	1866	6244	24882	10485	16344	59118	117073
Releases to atmosphere	0	-17321	-95258	-1824	-6101	-24314	-10246	-15971	-57770	
Net change	0	404	2223	43	142	567	239	373	1348	2670
Total (net sink/source)	639	74929	431180	182675	182353	84426	146212	133323	143108	689422
Average sink (Mg C ha^{-1} yr^{-1})	1.83	0.73	0.79	1.04	1.17	0.60	0.88	0.78	0.76	0.84

Table 2. Hypothetical C budget 'snapshot' of the Foothills Model Forest FMA area for 1988 (Mg C yr^{-1}), assuming no management after 1953.

	By Ecoregion				By Working Circle					FMA
	Montane	Subalpine	U. Boreal–Cordilleran	L. Boreal–Cordilleran	Athabasca	Marlboro	Embaras	McLeod	Berland	Total
Land area (ha)	350	102565	542383	175359	156506	140333	165784	170769	187265	820657
Forest biomass										
Net growth before disturbance	264	40127	356960	126934	116607	94011	98087	102476	113103	524284
Disturbance releases to atmosphere										
Natural (fire)	-60	-17298	-138169	-47247	-42039	-38788	-35955	-42241	-43751	-202774
Harvesting	0	0	0	0	0	0	0	0	0	0
Subtotal disturbance releases	-60	-17298	-138169	-47247	-42039	-38788	-35955	-42241	-43751	-202774
Disturbance transfers to soil										0
Natural (fire)	-141	-40391	-328322	-112268	-100084	-92708	-84725	-100301	-103305	-481122
Harvesting	0	0	0	0	0	0	0	0	0	0
Subtotal disturbance transfer	-141	-40391	-328322	-112268	-100084	-92708	-84725	-100301	-103305	-481122
Transfer to forest products	0	0	0	0	0	0	0	0	0	0
Net change	63	-17561	-109532	-32581	-25516	-37485	-22593	-40066	-33952	-159612
Forest soils										
Net detrital inputs before disturbance	-22	-23362	-165023	-53075	-46852	-45567	-40721	-54377	-53965	-241482
Disturbance transfer from biomass	141	40391	328322	112268	100084	92708	84725	100301	103305	481122
Disturbance releases to atmosphere										
Natural (fire)	-47	-12273	-88529	-29879	-26921	-24745	-23487	-28140	-27435	-130727
Harvesting	0	0	0	0	0	0	0	0	0	0
Subtotal disturbance releases	-47	-12273	-88529	-29879	-26921	-24745	-23487	-28140	-27435	-130727
Net change	72	4756	74770	29314	26310	22397	20517	17784	21905	108913
Forest products										
Transfer from biomass	0	0	0	0	0	0	0	0	0	0
Releases to atmosphere	0	0	0	0	0	0	0	0	0	0
Net change	0	0	0	0	0	0	0	0	0	0
Total (net sink/source)	135	-12805	-34761	-3267	795	-15089	-2076	-22282	-12047	-50699
Average sink (Mg C ha^{-1} yr^{-1})	0.39	-0.12	-0.06	-0.02	0.01	-0.11	-0.01	-0.13	-0.06	-0.06

The total uptake for the FMA as a whole in 1988 was approximately 0.7 Tg C yr^{-1} (1 Tg = 10^6 Mg = 1 megatonne). This net uptake was due mainly to increases in the biomass and soil C pools. At that time, net transfers of C to wood products were extremely small (about 2700 Mg C yr^{-1}); this is primarily because prior to 1988, most of the harvested material went into pulp products and landfill disposals. The studmill became operational only in 1972 and in the next 15 years (1973–1988) contributed about 10% of total wood products C during that period

The possible effects of natural disturbances on the FMA C budget are shown in Table 2. In this hypothetical C budget, it was assumed that in place of harvesting and wood processing, natural disturbances had been occurring with an average return interval of 50 years prior to 1988. Due to limitations in the available inventory data, we assumed that the forest age-class distribution was that previously reconstructed for 1953. In reality, the mean disturbance interval before 1953 was probably longer than 50 years. With the decrease in return interval after 1853, the hypothetical ecosystem was expected to be a net C source for some time after 1953 (as the average forest age decreased), probably persisting until past 1988.

Table 2 verifies this hypothesis, estimating the source to be a relatively small 0.06 Tg C yr^{-1}. For reasons discussed above, the Montane ecoregion would have been a net sink, but the remaining ecoregions would have been small net C sources. Interestingly, the area of the Athabasca working circle also appears as a net sink, possibly in part because it includes the Montane areas. We hypothesize therefore that, within the Athabasca working circle, large areas in other ecoregions were also disturbed in the period just before 1953.

These results are of interest primarily because they confirm that forest management (specifically protection against disturbances) can create a net C sink in a forest ecosystem which would otherwise be approximately carbon-neutral under natural conditions.

Retrospective/projective C Budget 1953–2238

Over the historical record for the region, the net effects of management appear to have increased C storage relative to that which would have occurred in its absence. While harvesting acts to reduce total ecosystem storage, the suppression of natural disturbances increases it more under most management scenarios we examined. Part of the reason for this is that most harvesting regimes simulated by the model are limited by the requirement that stands must carry 50 m^3 ha^{-1} to be considered operable. This therefore limits the decrease in C storage due to timber harvesting when harvesting rates are increased (see “Sensitivity analysis” below).

Management with harvesting clearly contributes to increased C storage when compared to the ‘unmanaged’ forest, assuming a fire return interval of 50 years. In the absence of silviculture, however, the overall gain now appears smaller than first reported in Price et al. (1996). Moreover, if longer natural disturbance intervals (75 or 100 years) are assumed, the gains from management diminish even further. Nevertheless, long-term gains in total C storage of at least 25% seem to be easily obtained.

Even with the baseline management scenario, (i.e., complete suppression of all natural disturbances, no gains from silviculture and FMP harvesting rates of 2,000,000 m^3 yr^{-1}), biomass C storage would not be sustainable without imposing the operability constraint on harvesting. Only in the "harvesting + silviculture" scenario (which assumes that density control of harvested stands results in increased biomass productivity) is the planned harvesting rate sustainable. In this latter case both a gradual long-term increase in the biomass C pool is possible and, in addition, continued transfers into the soil and wood products pools. The predicted long-term gains in total C storage for this case are around 50% compared to the unmanaged ecosystem with a 50-year disturbance interval.

The previous observation points to the need to study the effects of stand density control on the volume/biomass relationship. We emphasize that if increases in merchantable volume yield prove not to be accompanied by proportional increases in biomass yield, this does *not* mean merchantable volume production is not sustainable. Rather it implies that the increases in utilisable volume resulting from density control will result in less C being transferred to logging residues on-site and to the forest product sector.

This suggests also the need to examine the effect of improved wood utilizaiton on the net sector carbon budget. The potential to transfer a larger proportion of the harvest into construction lumber, with a lower average decay rate—resulting in increased product sector strorage—could provide some degree of offset to the potential ecosystem storage decrease noted in the previous paragraph. The exact consequences of improved wood utilisation on the C budget could be explored using CBM-CFS2.

Wood products contribute a relatively small fraction of total C storage, but the long-term accumulation of manufacturing residues and discarded pulp products creates an important storage pool. This assertion is subject to the caveats that the decomposition rates for landfilled materials are assumed to be correct, and in particular, that the environmental conditions governing decomposition in landfills do not change appreciably in the foreseeable future.

Sensitivity analysis

The effects of varying future harvesting by ±10% and ±25% of the planned level assumed in the baseline managed scenario showed that increased harvest levels reduce total storage, particularly in the short to medium term. But over time, as the younger faster-growing stands that replaced the relatively unproductive old-growth forest reach maturity, the long-term differences in total ecosystem carbon resulting from different harvesting levels gradually diminish. Again, this is partially explained by the operability constraint which ultimately limits the rate of harvesting to less than the planned rate. The only exception to this rule is where harvesting is reduced by 25% of the planned rate, in which case long-term ecosystem C storage is significantly increased. One of the issues hinted at in Price et al. 1997, is the economic value that might be placed on units of atmospheric C captured in living forest trees. If this value were to add significantly to the value placed on harvested timber, it would favour longer rotations. Extending the rotation age for maximum sustainable economic yield also has the effect of increasing the average C storage in the forest biomass.

Long-term soil C storage was found to be quite sensitive to changes in the assumed organic matter decomposition rate, with a 25% increase in decomposition causing about a 20% decrease in total ecosystem storage after 250 years. This is extremely important in the context of global warming, which would be expected to increase average soil decomposition rates. The effects of global warming would apply to both managed and umanaged systems, however. Thus, although both would lose soil C, all other factors being equal, the protected managed forest ecosystem would still store more C than the unmanaged forest subjected to uncontrolled natural disturbances.

Not surprisingly, increased disturbances resulted in significant decreases in total C storage. Hence successful protection against fires and insect pests, which increases the natural disturbance interval, will also have a significant benefit by increasing ecosystem C.

Finally, in another important sensitivity test, the effects of adding a natural disturbance regime to the planned harvesting rates was investigated. Where natural disturbances are assumed to occur without any protection efforts, harvesting clearly reduces total C storage (in the ecosystem plus wood products). An important observation arising from this (Price et al. 1997) is as follows: In order for total C storage in the managed ecosystem to remain at levels comparable to those which would be expected assuming natural disturbances with a 50-year return interval, and yet allow planned harvesting rates, it is estimated that protection measures must be sufficient to extend this interval to at least 100 years (see Appendix II). Based on our assessment of the age-class distribution, the average return interval was about 93 years in 1988, which suggests that a management objective of maintaining a 100-year return interval for natural disturbances may be achievable. In any case, such an estimate does not allow for the possibility that some the planned harvest could obtained through salvaging timber from disturbed stands.

The results of all the 17 simulations (baseline runs and sensitivity tests) on total C stocks in the entire FMA area (including wood products C for those scenarios involving harvesting), are presented in a summary table (Appendix II, Price et al. 1997, Table 2). Total C storage, projected for 50, 100 and 150 years beyond 1953, is reduced by increased harvesting, but plausible increases in the natural disturbance interval lead to much larger reductions. Gains from stand density control lead to significant increases in total C storage (relative to the baseline managed scenario), in the longer term (about 13% after 150 years).

Further Work/Concluding Remarks

GHG emissions from mill

The above analysis does not consider the emission of CO_2 and other greenhouse gases from Weldwood's forest management and harvesting operations, nor those associated with wood processing operations in the mills. This is primarily because we have experienced continued difficulties in obtaining basic fuel consumption data from Weldwood. It is probably reasonable to assume that the fossil energy consumption associated with forest operations and sawmilling represents a relatively small fraction of the current annual net uptake of CO_2 by the forest ecosystem, but hard data would be an invaluable substitute for this assumption. Weldwood have provided data on emissions from the pulpmill, which only partially support the calculations reported in Price et al. (1996). Part of the contradiction probably results from the time-frame over which the new data were collected (1990–1991) compared to that covered by the Weldwood DFMP, which was based on data obtained in the period prior to 1990 (Weldwood 1991). Since that date, production of pulp has increased significantly, while emissions have generally decreased (Table 3).

Table 3. Total air-dry kraft pulp production and C emissions from Weldwood's Hinton pulpmill, 1990-1995. (Source: Weldwood).

	1990	1991	1992	1993	1994	1995	Mean
Finished pulp production (Mg)	232297	256760	372282	363586	378545	394219	332948
C emissions from pulpmill (Mg)	74758	58821	60919	63462	64009	61283	63875
C emitted/Pulp Produced (Mg [C] Mg^{-1} [Pulp])	0.322	0.229	0.164	0.175	0.169	0.155	0.202
Energy consumed:							
natural gas (Mg C)	56555	44141	45717	47677	47677	45835	47934
waste wood (Mg C)	37917	42512	43952	43977	58913	49755	46171
spent pulp liquor (Mg C)	187247	261164	276175	271276	270555	285168	258597
Total energy consumed (Mg C)	281718	347817	365844	362930	377145	380757	352702
Fossil C/Total Fuel C	0.201	0.127	0.125	0.131	0.126	0.120	0.138
Fossil C used (Mg [C] Mg^{-1} [Pulp])	0.243	0.172	0.123	0.131	0.126	0.116	0.152

According to CPPA, the Canadian national average release of CO_2 for kraft pulp was close to 2 Mg [CO_2] Mg^{-1} [Pulp] in 1988 (CPPA 1991), corresponding to approximately 0.75 Mg [C] Mg^{-1} [Pulp]. Weldwood's pulp operation was modernised recently, however, so it is likely to be more efficient, as Table X indicates. Thus, even in 1990, the release was less than half the 1988 national average, and it decreased steadily up to 1995. In 1988, according to CPPA, approximately 75% of national C emissions from pulp production were contributed by the raw material with the balance coming from fossil fuels (i.e., < 0.2 Mg [C] Mg^{-1} [Pulp]). Weldwood's DFMP reported that in 1992, approximately 75% of the plant's energy requirements were met from byproducts, with only 25% coming from natural gas and diesel fuel (implying fossil fuel emissions on the order of 15% of total). But Weldwood's annual statistics for the period 1990–1995 give a mean annual emission of approximately 63,875 Mg [C] yr^{-1} from all sources, whereas consumption of natural gas averaged 47,900 Mg [C] yr^{-1}. It is reasonable to assume that combustion of natural gas will be complete, implying that on average, about 75% of C emissions are from fossil sources, a fraction that proved extremely conservative over the 6-year period.

The major problem is that a very much larger portion of the C contained in the consumed fuel was evidently not released to the atmosphere during consumption. In 1995, the total C contained in all fuels (natural gas, waste wood and spent pulp liquor) is estimated to be about 380,000 Mg C, but only about 62,000 Mg C were released as CO_2 and CH_4. Where did the remaining 320,000 Mg C go? In 1995, the only year for which data were available, Weldwood landfilled about 30,000 m^3 of waste material. Even if this were 75% elemental C, it could not explain the discrepancy. [One possibility is that much of the 320,000 Mg C is actually in finished products: i.e., it is "consumed", but not oxidised; another is that spent pulp liquor consists largely of the breakdown products of chemical additives originating from sources outside the FMA.]

Until we can unravel these discrepancies, any attempt to provide a comprehensive assessment of C emissions from the wood processing operations will remain suspect. It does seem clear, however, that C emissions from fossil fuel sources *alone* are relatively small compared to the current annual net uptakes estimated from the managed scenarios. An annual average emission of 50,000 Mg C yr^{-1} (= 0.05 Tg C yr^{-1}) compares to the current net uptake (1988) by the ecosystem and forest products pool of 0.7 Tg C yr^{-1} (Table 1).

Allometry of lodgepole pine

Due to other commitments, we were unable to perform field comparisons of biomass production between stands regenerated following harvesting, and those regenerated following fire. This remains an important question to pursue. Two sets of measurements are contemplated. Firstly, total ecosystem C storage (biomass, litter, coarse woody debris and soils) requires to be compared in similarly aged lodgepole pine stands of fire- and harvest-origin growing on similar sites. This could be performed at the Gregg River fire site, to build on measurements already being undertaken there. Secondly, it is desirable to obtain allometric data to develop relationships to convert Weldwood yield curves from merchantable stem volume estimates to total aboveground biomass. This will require non-destructive tree measurements in some of the Weldwood Permanent Sample Plots (PSPs), and a small number of destructive measurements made on trees taken from outside the PSPs.

Effects of climate change

Projections of ecosystem responses under a changing climate are subject to the particular problem that statistical models which predict forest growth for a given site may no longer be valid in the future, because the environmental conditions which characterise that site will also have changed. Consequently, it is necessary to develop more process-based ecosystem models that can respond realistically to the changed conditions. One approach being pursued in related work is to adapt forest patch models to enable them to generate biomass-over-age curves for use by CBM-CFS2. The output can be validated against field measurements under current climate conditions, and the patch models can then be used to simulate forest responses under GCM-projections of future climate. The output is used to generate biomass growth curves which should be more appropriate for the prescribed future conditions (though of course, these may prove unrealistic). The Weldwood PSP database and the derived YCs could be particularly useful for validating such projections, particularly if available in GIS format.

Climatic change is likely to affect processes other than growth, including soil and litter decomposition and the incidence of natural disturbances such as wildfire and insect attacks. The latter will require additional modelling effort if credible assessments of ecosystem responses to global warming are to be made.

Linkage to GIS/DSS

By now the 1993 Forest Inventory should be complete, and the data entered into the Foothills Forest GIS. The opportunity therefore exists to overlay these data with the ecosystem classification and achieve a better correspo0ndence between ecoregions, soil groups and forest stands, at the sub-compartment level. In addition, it should be possible to overlay digital topographic data and climate records from local climate stations to obtain a higher resolution mapping of temperature and precipitation distributions, both in the Model Forest and in the neighbouring Jasper National Park. This would allow a higher resolution assessment of C dynamics within Foothills Forest. Such a development would also permit validation of stand-level ecosystem simulators (e.g., forest patch models) which could then be applied to the JNP area to generate simulated biomass-over-age relationships. When combined with knowledge of the disturbance history in the JNP, forest ecosystem C dynamics could also to be estimated for the Park area.

It has been a stated hope of the project that the C budget analysis could at some point form a component of the Foothills Forest management decision support tool (DST). As an initial step, the format of the input and output files used and generated by CBM-CFS2 required to be documented. This has now been done, with a report included as Appendix III.

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Price, D.T., R.M. Mair, W.A. Kurz and M.J. Apps. 1996. Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study. In: M.J. Apps and D.T. Price (eds.) *Forest Ecosystems, Forest Management and the Global Carbon Cycle*. NATO Advanced Science Institutes series, Vol. **I40**, Springer-Verlag, Heidelberg, pp. 279–292.

Price, D.T., M.J. Apps, W.A. Kurz, M. Wesbrook and R.S. Curry. 1994. A "Model Forest Model": Steps towards detailed carbon budget assessments of boreal forest ecosystems. *World Resour. Rev.* **6**: 461–476.

Price, D.T., S.R. Curry, D.H. Halliwell, M.J. Apps and W.A. Kurz. 1997. Comprehensive assessment of carbon stocks and fluxes in a boreal forest management unit. *Can. J. Forest Research* (In Press).

Price, D.T., M.J. Apps and W.A. Kurz. 1997 Past and Future Carbon Dynamics of Canada's Forestry Sector. (Presented at workshop: "Carbon Mitigation Potentials of Forestry and the Wood Industry", Munich, June 1996, accepted for publication in peer-reviewed workshop proceedings.)

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Appendix I: Road Map for Data Disks

Attached with this report are a set of DOS format 1.44 MB floppy diskettes containing Excel 5 spreadsheets summarising output from all 17 runs. Each disk contains a single self-extracting archive file, which when unzipped yields three Excel 5 spreadsheet files. These three spreadsheets contain data for a single run of the CBM-CFS2, including 35 graphs. This appendix records how the files are named, what each of the three files contains, and how the graphs are laid out.

File names

File names conform to a convention of two or three letters ('AGE', 'FL' or 'PS') usually followed by two digits, a hyphen, a third digit and a final letter. The only exception is for one set of files which have the letters 'SIL' in place of the two digits and hypen. All files contain original output data, for each of the 14 spatial units indentified in the FMA area. The following table gives the names of all files included in the floppy disk archive, including their sizes and dates and times of last editing, which can be checked against the extracted files.

FILE NAME	SIZE (	DATE	TIME	FILE NAME	SIZE (	DATE	TIME	FILE NAME	SIZE (	DATE	TIME
AGE53-2C.XLS	1,374,208	11/12/96	16:06	FL53-2C.XLS	805,888	30/01/97	15:15	PS53-2C.XLS	315,392	07/11/96	11:15
AGE53-2D.XLS	1,355,264	19/09/96	14:24	FL53-2D.XLS	764,416	20/09/96	10:35	PS53-2D.XLS	337,920	07/11/96	9:50
AGE53-2E.XLS	1,350,656	19/09/96	14:26	FL53-2E.XLS	765,440	20/09/96	10:38	PS53-2E.XLS	336,384	07/11/96	9:50
AGE53-2F.XLS	1,363,968	19/09/96	14:27	FL53-2F.XLS	764,416	20/09/96	10:47	PS53-2F.XLS	338,944	07/11/96	9:51
AGE53-2G.XLS	1,359,360	19/09/96	14:38	FL53-2G.XLS	764,416	20/09/96	10:50	PS53-2G.XLS	338,432	07/11/96	9:52
AGE88-1A.XLS	1,291,264	11/12/96	14:50	FL88-1A.XLS	775,680	20/09/96	10:20	PS88-1A.XLS	257,536	11/12/96	17:03
AGE88-1B.XLS	1,343,488	19/09/96	14:42	FL88-1B.XLS	793,088	06/11/96	15:55	PS88-1B.XLS	346,624	30/12/96	16:22
AGE88-1C.XLS	1,345,536	19/09/96	14:45	FL88-1C.XLS	775,680	20/09/96	10:24	PS88-1C.XLS	347,136	07/11/96	9:33
AGE88-1D.XLS	1,342,976	19/09/96	14:46	FL88-1D.XLS	776,192	20/09/96	10:27	PS88-1D.XLS	346,624	07/11/96	9:34
AGE88-1E.XLS	1,339,904	19/09/96	14:48	FL88-1E.XLS	776,704	20/09/96	10:28	PS88-1E.XLS	346,624	07/11/96	9:38
AGE88-1F.XLS	1,358,336	19/09/96	14:49	FL88-1F.XLS	849,408	20/09/96	10:20	PS88-1F.XLS	348,160	07/11/96	9:40
AGE88-1G.XLS	1,354,240	19/09/96	14:51	FL88-1G.XLS	847,872	30/01/97	11:29	PS88-1G.XLS	348,160	07/11/96	9:42
AGE88-1H.XLS	1,352,192	19/09/96	14:53	FL88-1H.XLS	846,336	20/09/96	10:24	PS88-1H.XLS	348,160	07/11/96	9:43
AGE88-2A.XLS	1,363,456	19/09/96	14:54	FL88-2A.XLS	813,056	20/09/96	10:13	PS88-2A.XLS	347,648	07/11/96	9:44
AGE88-2B.XLS	1,360,384	19/09/96	15:01	FL88-2B.XLS	863,744	30/01/97	15:40	PS88-2B.XLS	383,488	30/01/97	14:44
AGE88-2C.XLS	1,357,824	19/09/96	14:58	FL88-2C.XLS	851,456	20/09/96	10:17	PS88-2C.XLS	293,376	06/11/96	16:51
AGESIL1A.XLS	1,339,392	19/09/96	14:59	FLSIL1A.XLS	775,680	20/09/96	10:26	PSSIL1A.XLS	313,344	11/12/96	17:34

File contents

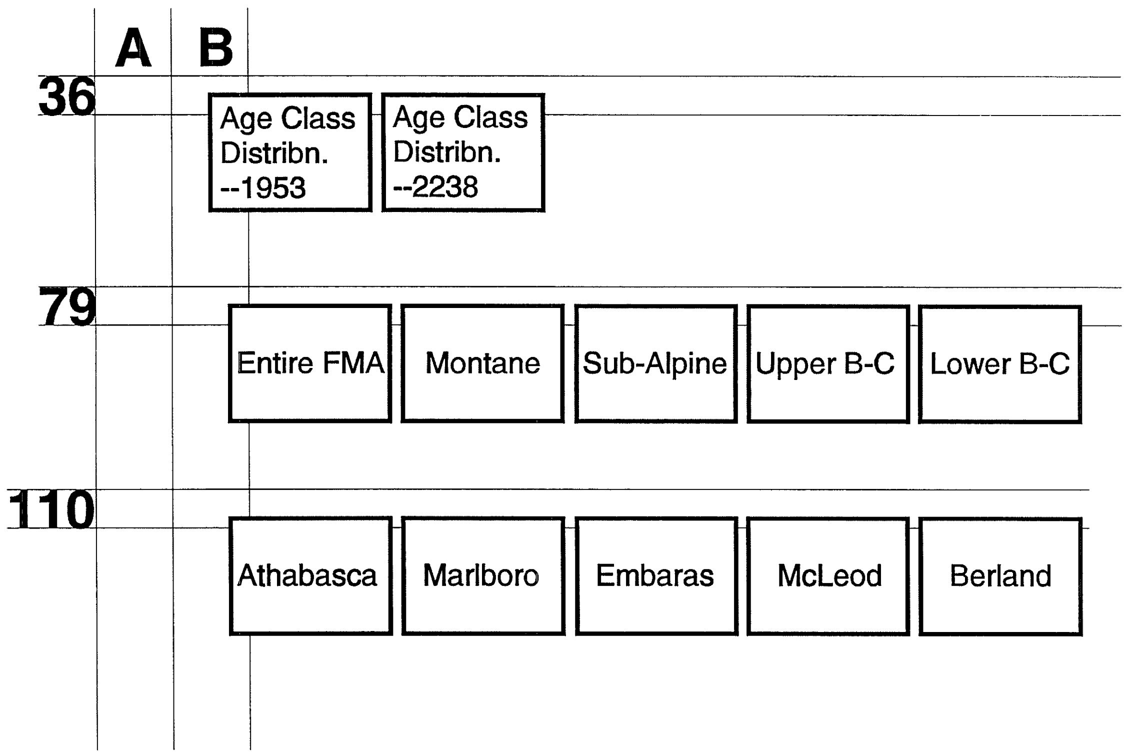
The AGE*.XLS files derive from the CBM-CFS2 AGEIND.OUT output file, containing estimates of C storage per hectare, broken down into 5-year age classes. The FL*.XLS files derive from the FLUXIND.OUT output file, containing estimates of C fluxes from different pools at five year intervals, broken down by disturbance types. The PS*.XLS files derive from the POOLIND.OUT output file, containing estimates of total pool storage at five year intervals. The subsequent letters and digits in each file name, identify the indvidual runs, as follows. In the following table, the letters A and B used to identify the run descriptions, denote managed and un-managed scenarios respectively, as reported in the draft paper submitted to *Canadian Journal of Forest Research*, Appendix II):

CODE	RUN DESCRIPTION	COMMENTS
88-1A	A. MANAGED, NO FIRES, FROM 1953	Protection from fires and insects.
	Sensitivity tests:	
88-1B	A3. Increase harvesting rate in 1988 by 10%	Protection from fires and insects.
88-1C	A4. Increase harvesting rate in 1988 by 25%	Protection from fires and insects.
88-1D	A2. Reduce harvesting rate in 1988 by 10%	Protection from fires and insects.
88-1E	A1. Reduce harvesting rate in 1988 by 25%	Protection from fires and insects.
88-1F	A9. Natural disturbances with average interval of 50 yr starting 1988	Assume no disturbances prior to 1988; harvesting as recorded.
88-1G	A10. Natural disturbances with average interval of 75 yr starting 1988	Assume no disturbances prior to 1988; harvesting as recorded.
88-1H	A11. Natural disturbances with average interval of 100 yr starting 1988	Assume no disturbances prior to 1988; harvesting as recorded.
88-2A	A6. Natural disturbances with average interval of 50 yr starting 1953	Harvesting as recorded since 1953.
88-2B	A7. Natural disturbances with average interval of 75 yr starting 1953	Closest to true disturbance history; harvesting as recorded since 1953.
88-2C	A8. Natural disturbances with average interval of 100 yr starting 1953	Harvesting as recorded since 1953.
88SIL	A5. Increase productivity for all harvested stands	100% harvest + silviculture + protection from fires and insects.
53-2C	B. UNMANAGED, NO HARVESTING, FROM 1953	50 yr disturbance interval, no management or harvesting.
	Sensitivity tests:	
53-2D	B1. Increase natural disturbance interval to 75 yr	No management or harvesting.
53-2E	B2. Increase natural disturbance interval to 100 yr	No management or harvesting.
53-2F	B3. Increase soil decomposition rate by 25%	No management or harvesting.
53-2G	B4. Decrease soil decomposition rate by 25%	No management or harvesting.

Graphs layout

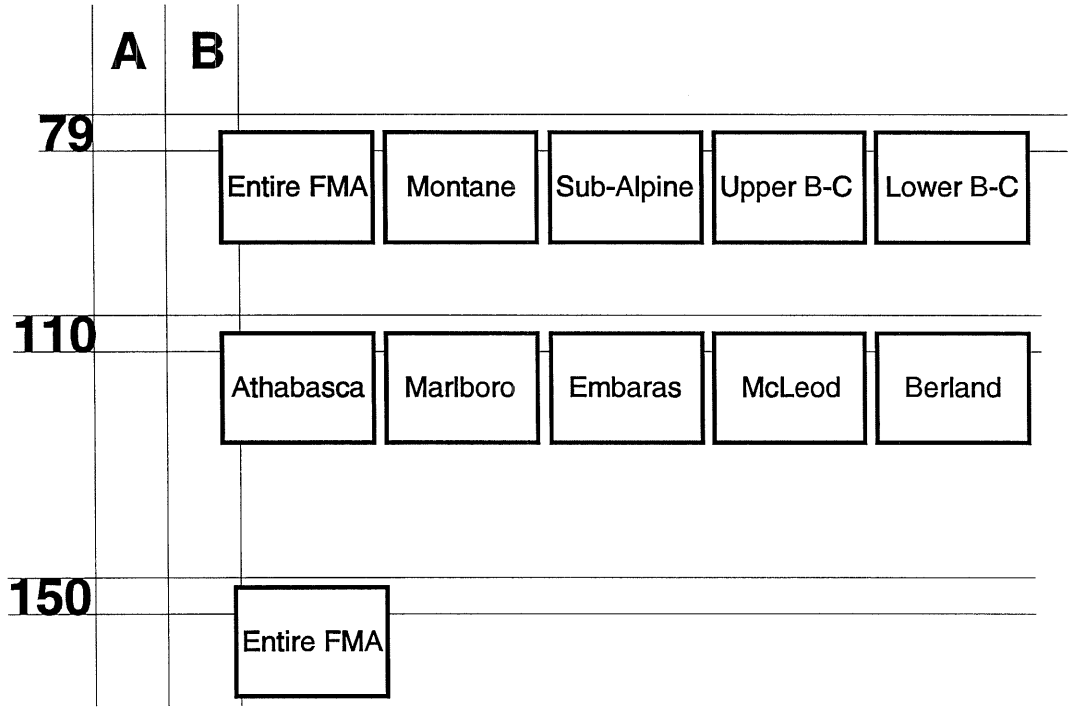
Each of the three file types, AGE*.XLS, FL*.XLS and PS*.XLS contains 11 or 12 graphs which are positioned over the raw input data.

AGE*.XLS contain 12 graphs laid out as follows:



The first two graphs provide simulated age-class distributions for the FMA at the beginning and end of the simulation. (Since all simulations start with the same data in 1953, the first of these should be identical for all simulations). The remaining graphs show time courses of mean carbon storage density for the main pools over the duration of the simulation. The upper row of five provides this information for the entire FMA and grouped for each of the four ecoregions, in the order Montane, Subalpine, Upper Boreal–Cordilleran, Lower Boreal–Cordilleran. The lower row provides similar information grouped by working circle, in the order Athabasca, Marlboro, Embaras, McLeod, Berland.

FL*.XLS and PS*.XLS contain 11 graphs each, laid out as follows:



The first two rows of five graphs show time courses of annual C flux (FL*.XLS) and total C storage (PS*.XLS) for the main pools, including products where applicable, over the duration of the simulation. The upper row provides this information for the entire FMA and grouped for each of the four ecoregions, in the order Montane, Subalpine, Upper Boreal–Cordilleran, Lower Boreal–Cordilleran. The lower row provides similar information grouped by working circle, in the order Athabasca, Marlboro, Embaras, McLeod, Berland. The final graph is a duplicate of the first graph (entire FMA) formatted for printing on paper.

Appendix II

Reprints of published papers and submitted manuscripts

Price, D.T., M.J. Apps, W.A. Kurz, M. Wesbrook and R.S. Curry. 1994. A "Model Forest Model": Steps towards detailed carbon budget assessments of boreal forest ecosystems. *World Resour. Rev.* **6**: 461–476.

Price, D.T., R.M. Mair, W.A. Kurz and M.J. Apps. 1996. Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study. In: M.J. Apps and D.T. Price (eds.) *Forest Ecosystems, Forest Management and the Global Carbon Cycle.* NATO Advanced Science Institutes series, Vol. **I40**, Springer-Verlag, Heidelberg, pp. 279–292.

Price, D.T., S.R. Curry, D.H. Halliwell, M.J. Apps and W.A. Kurz. 199?. Comprehensive assessment of carbon stocks and fluxes in a boreal forest management unit. *Can. J. Forest Research* (In press).

Price, D.T., M.J. Apps and W.A. Kurz. 1997? Past and Future Carbon Dynamics of Canada's Forestry Sector. (Presented at workshop: "Carbon Mitigation Potentials of Forestry and the Wood Industry", Munich, June 1996, accepted for publication in peer-reviewed workshop proceedings.)

File Documentation and Performing Runs with the CBM-CFS2 (Object Oriented Version)

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Summary: This document describes how to run the C++ version of the CBM-CFS2 model, a number of the utilities and subroutines in it, and the input and output data files used by it. The C++ version (Object Oriented code) was developed form the original microsoft BASIC code in order to 1) speed up computations 2) make better use of computer memory and resources and 3) to facilitate transportability of the code to other platforms (specifically the UNIX operating system used by SPARC workstations.

In this document computer filenames and instructions are in arial font: arial. Unix command prompts are shown as the symbol %. Generic filenames are in italized arial fonts: *<filename>*.

NB Should problems be encountered, please forward these to mapps@nofc.forestry.ca

1. Compiling the Model

The process of compiling the Object-Oriented Carbon Budget Model is fairly simple thanks to UNIX's convenient make utility. The program make accepts an input file entitled makefile containing instructions on how to compile a program.

Should the source code be provided in an archived, compressed file--this would be indicated by an extension of .tar.Z--it will be necessary to extract the contents. First, decompress the package by entering

```
%uncompress <filename>.tar.Z
```

where *filename* is the name of the archive.
Next, remove the contents of the package by typing

[1] JP Samson performed the code conversion from BASIC to C++ while under Dr Apps' supervision at NoFC as a summer student 1993–94 and as a IIASA Young Summer Scientist 1995. He is presently a graduate student at University of Alberta in Computer Science.

[2] R Mair was the Carbon Modelling technician at NoFC under Dr Apps' supervision. Present address: Corrections Canada, Edmonton.

```
%tar -xvf <filename>.tar
```

This will install the revision control system directory RCS containing the source code and headers, and a file entitled makefile in the current working directory.

Now, to compile the code, simply enter

```
%make
```

This will create the executable model, cbm, and a special sorting utility, sort.
The make utility is smart--if some of the code is changed, it will only recompile the modules affected by the modification. (However, the programmer must take care to alter the dependencies described in makefile if necessary).

There are a few extra handy features implemented in the provided makefile. To delete the temporary object code (the files terminated with a .o extension), type

```
%make clean
```

To delete all the source code and headers (that is, the files with suffixes of .cc and .h), enter:

```
%make cleancode
```

2. Why Make Changes to the Input Files?

There are several strong reasons why it was decided to alter the format of several of the input and output files associated with the Carbon Budget Model. First, some of the input files are in binary format. Although more efficient and compact, a binary file is not generally compatible across different computer platforms due to differences in the format of the various variable types. An ASCII version not only alleviates this problem but provides the additional convenience of being humanly readable.

When implementing an object-oriented design of the model, it is desirable for input files to contain data specifically applicable to individual classes rather than hold information of concern to several potentially unrelated objects. Such a scheme emphasizes the "black box" nature of classes. Some input files have been decomposed to ensure that only data specific to the needs of individual classes are enclosed within each input file.

Finally, in order to ease the parsing, extra fields were added to some input files. In addition, one unique input file has been introduced to take advantage of the new features in the object-oriented model.

3. Providing the Correct Input Files to the Model

3.1. The Directory Paths File

The configuration file in the BASIC model, cb.cfg, contains the directory paths for input, temporary, and output files, the time step information, the tolerances used in deciding state variable object merge candidates, and sensitivity analysis multipliers. It is apparent that the configuration file contains components are unrelated and should be decomposed into additional input files. This is certainly more convenient for the classes used in the Object-Oriented Carbon Budget Model.

The file paths.inf contains the directory paths to use for all input and output files (with the exception of the merge suitcase file which is described later). The contents are:

Line 1: <input file directory path>

Line 2: <temporary file directory path>

Line 3: <output file directory path>

The appropriate directory path string is used as a prefix for an input or output file, so these lines must be terminated with a slash ('/'). Currently, no temporary files are created so the temporary file path is unimportant. If any of these lines are empty, the current working directory is assumed.

It is not necessary to include the paths.inf file--if missing, the current working directory is used for all input and output files. If it does exist, the directory paths file must reside in the current working directory when the model is executed.

3.2. The Model Time Step File

The number of time steps to iterate through and the size of each of these time steps (in years) is the data contained in the model file model.inf.

Line 1: <time step size> <number of time steps>

If model.inf does not exist in the input directory (as specified in the directory paths file), the default time step size of five years and one time step is assumed.

3.3. The Spatial Unit/Disturbance Group File

The file reclass.lst contains information concerning the disturbance types, spatial units, and disturbance groups involved in the simulation. The contents have been slightly modified for use with the object-oriented model.

Line 1: <description>

Line 2: <description>

Line 3: <flag reflecting whether the future database should be transferred to the current after each disturbance pass (unused)>

Line 4: *<number of disturbance types>*

Line 5: *<disturbance type id>* *<disturbance type id>* ... *<disturbance type* id>

Line 6: *<number of spatial units>*

Line 7-n: <spatial unit id> <province id> <ecoclimatic province id> <status> <disturbance group id> <disturbance group id> ... <disturbance group id>

In lines five and seven, the number of disturbance types/groups input is given in line four. The number of spatial units indicated in line six dictates the number of subsequent lines containing spatial unit information. The first disturbance group on a spatial unit line corresponds with the first disturbance type on line five. This is the group to which the spatial unit belongs for a particular disturbance type.

3.4. The Indicator Information File

The indicator information file, indicate.inf, has been introduced to conveniently choose whether an ecocheck file is to be produced during a model run.

Line 1: <produce ecocheck file>

A value of 0 means that no ecocheck file will be created. Any other integer suggests that an ecocheck file should be made.The indicator information file is optional. If omitted, an ecocheck file will automatically be produced.

3.5. Biomass to Carbon Multipliers File

The biomass-to-carbon multipliers within the input file biotoc.dat are used to convert between biomass and carbon units for each species' components. The format remains unchanged from the BASIC version.

Line 1: <softwood merchantable multiplier> <description>

Line 2: <softwood foliage multiplier> <description>

Line 3: <softwood other multiplier> <description>

Line 4: <softwood submerchantable multiplier> <description>

Line 5: <softwood coarse root multiplier> <description>

Line 6: <softwood fine root multiplier> <description>

Line 7: <hardwood merchantable multiplier> <description>

Line 8: <hardwood foliage multiplier> <description>

Line 9: <hardwood other multiplier> <description>

Line 10: <hardwood submerchantable multiplier> <description>

Line 11: <hardwood coarse root multiplier> <description>

Line 12: <hardwood fine root multiplier> <description>

3.6. The Biomass Carbon Ratios File

The attributes of the functions that determine the proportion of carbon devoted to each species' components for each spatial unit is contained in the biomass carbon ratios file bioratio.dat. The object-oriented model uses an updated version that includes attributes for root components that were hardcoded into the BASIC model.

Line n: <spatial unit id> <species id> <merchantable ratio y-intercept> <merchantable ratio slope> <foliage ratio y-intercept> <foliage ratio slope> <other ratio y-intercept> <other ratio slope> <submerchantable ratio y-intercept> <submerchantable ratio slope> <coarse root ratio y-intercept (unused)> <coarse root ratio slope (unused)> <fine root ratio y-intercept> <fine root ratio slope> <ratio of root to total biomass y-intercept> <ratio of root to total biomass slope>

There must be a sufficient number of entries in the biomass carbon ratios file for all species in all spatial units. The merchantable, foliage, other, and submerchantable attributes describe a linear function. The fine root attributes are used with a logarithmic function. The ratio of root to total biomass attributes describe a linear function for the softwood species and a logarithmic function for the hardwood species.

The constant values for the root carbon ratio functions should have (as taken from the BASIC model) a coarse root ratio slope and intercept of 0.0, a fine root ratio y-intercept of 0.924 and slope of -0.822, and a ratio of root to total biomass y-intercept of 0.0 and slope 0.23281.

3.7. The Climate (Temperature and Precipitation) Files

The climate files contain the average temperature or precipitation in each spatial unit for each time step. These files are entitled temp.out and prec.out respectively and are unchanged in the object-oriented model.

Line 1: <description>

Line 2: <climate variability> <projection> <slope type> <randomness> <spread> <year of carbon dioxide> <number of spatial units> <time step size>

Line 3, 4-n: <time step number> <spatial unit climate> <spatial unit climate> ... <spatial unit climate>

The number of spatial units and time step size given in line two should be the same as those given in the spatial unit/disturbance group file, reclass.lst, and the model time step file, model.inf, respectively. Line three is the base climate values (i.e. the climate for the "nonexistent" zeroth time step). There must subsequently be as many spatial unit climate lines as spatial units.

3.8. THE CLIMATE CHANGE MULTIPLIERS FILE

In the BASIC model the file misc.lst features multipliers that effect growth, and the area influenced by insect and fire disturbances based on the climate. These multipliers have been moved to a more appropriate file entitled ccdist.inf.

Line 1: <climate change effect on growth y-intercept> <climate change effect on growth slope>

Line 2: <temperature change effect on fire y-intercept> <temperature change effect on fire slope> <temperature change effect on insects y-intercept> <temperature change effect on insects slope>

Line 3: <precipitation change effect on fire y-intercept> <precipitation change effect on fire slope> <precipitation change effect on insects y-intercept> <precipitation change effect on insects slope>

All these attributes describe linear functions which return the appropriate multipliers based on the current temperature and precipitation.

3.9. THE SOIL DEFINITION FILE

The soil definition file, soildef2.inf, holds turnover and decay data for soil pools. The only difference between this file and its BASIC counterpart is the name; originally it was entitled soildef2.dat.

Line 1: <softwood foliage turnover proportion in Arctic> <softwood foliage turnover proportion in Subarctic> <softwood foliage turnover proportion in Boreal> <softwood foliage turnover proportion in Coast Temperate> <softwood foliage turnover proportion in Moderate Temperate> <softwood foliage turnover proportion in Grassland> <softwood foliage turnover proportion in Subarctic Cordilleran> <softwood foliage turnover proportion in Cordilleran> <softwood foliage turnover proportion in Interior Cordilleran> <softwood foliage turnover proportion in Pacific Cordilleran> <softwood foliage turnover proportion in East Boreal>

Line 2: <hardwood foliage turnover proportion in Arctic> <hardwood foliage turnover proportion in Subarctic> <hardwood foliage turnover proportion in Boreal> <hardwood foliage turnover proportion in Coast Temperate> <hardwood foliage turnover proportion in Moderate Temperate> <hardwood foliage turnover proportion in Grassland> <hardwood foliage turnover proportion in Subarctic Cordilleran> <hardwood foliage turnover proportion in Cordilleran> <hardwood foliage turnover proportion in Interior Cordilleran> <hardwood foliage turnover proportion in Pacific Cordilleran> <hardwood foliage turnover proportion in East Boreal>

Line 3: <stem turnover proportion in Arctic> <stem turnover proportion in Subarctic> <stem turnover proportion in Boreal> <stem turnover proportion in Coast Temperate> <stem turnover proportion in Moderate Temperate> <stem turnover proportion in Grassland> <stem turnover proportion in Subarctic Cordilleran> <stem turnover proportion in Cordilleran> <stem turnover proportion in Interior Cordilleran> <stem turnover proportion in Pacific Cordilleran> <stem turnover proportion in East Boreal>

Line 4: <softwood branch turnover proportion in Arctic> <softwood branch turnover proportion in Subarctic> <softwood branch turnover proportion in Boreal> <softwood branch turnover proportion in Coast Temperate> <softwood branch turnover proportion in Moderate Temperate> <softwood branch turnover proportion in Grassland> <softwood branch turnover proportion in Subarctic Cordilleran> <softwood branch turnover proportion in Cordilleran> <softwood branch turnover proportion in Interior Cordilleran> <softwood branch turnover proportion in Pacific Cordilleran> <softwood branch turnover proportion in East Boreal>

Line 5: <hardwood branch turnover proportion in Arctic> <hardwood branch turnover proportion in Subarctic> <hardwood branch turnover proportion in Boreal> <hardwood branch turnover proportion in Coast Temperate> <hardwood branch turnover proportion in Moderate Temperate> <hardwood branch turnover proportion in Grassland> <hardwood branch turnover proportion in Subarctic Cordilleran> <hardwood branch turnover proportion in Cordilleran> <hardwood branch turnover proportion in Interior Cordilleran> <hardwood branch turnover proportion in Pacific Cordilleran> <hardwood branch turnover proportion in East Boreal>

Line 6: <reference decay rate for very fast pool> <reference decay rate for fast pool> <reference decay rate for medium pool> <reference decay rate for slow pool>

Line 7: <reference decay rate temperature for very fast pool> <reference decay rate temperature for fast pool> <reference decay rate temperature for medium pool> <reference decay rate temperature for slow pool>

Line 8: <q10 value for very fast pool> <q10 value for fast pool> <q10 value for medium pool> <q10 value for slow pool>

Line 9: <hardwood decay as a proportion of softwood decay>

Line 10: <softwood coarse root turnover proportion> <softwood fine root turnover y-intercept> <softwood fine root turnover slope>

Line 11: <hardwood coarse root turnover proportion> <hardwood fine root turnover y-intercept> <hardwood fine root turnover slope>

Line 12: <softwood maximum decay rate multiplier for very fast pool> <softwood maximum decay rate multiplier for fast pool> <softwood maximum decay rate multiplier for medium pool>

Line 13: <hardwood maximum decay rate multiplier for very fast pool> <hardwood maximum decay rate multiplier for fast pool> <hardwood maximum decay rate multiplier for medium pool>

Line 14: <proportion of very fast pool to air> <proportion of fast pool to air> <proportion of medium pool to air> <proportion of slow pool to air> <proportion of peat pool to air>

Line 15: <peat addition> <peat loss>

3.10. THE DISTURBANCE ACTIONS FILE

The various disturbances to be applied during a model run are indicated in the disturbance actions file disturb.lst. The contents of this file remain the same in the object-oriented implementation of the model.

There are two difference versions of disturbance action file; the type is indicated by a field in the file. In the first version, all disturbances are listed in sequence. The second file type has the disturbances grouped by time step in which they are exclusively applied. (In the case of disturbances grouped by time step, their time range must lie entirely within the time step.)

An example of the first type of disturbance actions file follows:

Line 1: <description>

Line 2: <description>

Line 3: <file type> = 1

Line 4-n: <disturbance type id> <disturbance group> <start year> <end year> <efficiency> <sort type id> <target type id> <area target> <merchantable C target> <proportional target> <option A softwood management type> <option A hardwood management type> <option A softwood growth curve id> <option A hardwood growth curve id> <option A stocking> <option A land type> <option B softwood management type> <option B hardwood management type> <option B softwood growth curve id> <option B hardwood growth curve id> <option B stocking> <option B land type> <minimum biomass C eligibility> <maximum biomass C eligibility> <minimum merchantable C eligibility> <maximum merchantable C eligibility> <minimum softwood merchantable C eligibility> <maximum softwood merchantable C eligibility> <minimum hardwood merchantable C eligibility> <maximum hardwood merchantable C eligibility> <minimum softwood maturity eligibility> <maximum softwood maturity eligibility> <minimum hardwood maturity eligibility> <maximum hardwood maturity eligibility> <minimum softwood management type eligibility> <maximum softwood management type eligibility> <minimum hardwood management type eligibility> <maximum hardwood management type eligibility> <minimum softwood growth curve id eligibility> <maximum softwood growth curve id eligibility> <minimum hardwood growth curve id eligibility> <maximum hardwood growth curve id eligibility> <minimum stocking eligibility> <maximum stocking eligibility> <minimum land type eligibility> <maximum land type eligibility>

The second version of disturbance actions file is a little more complex as shown below:

Line 1: <description>

Line 2: <description>

Line 3: <file type> = 2

Line 4: <number of actions in time step>

Line 5-n: <disturbance type id> <disturbance group> <start year> <end year> <efficiency> <sort type id> <target type id> <area target> <merchantable C target> <proportional target> <option A softwood management type> <option A hardwood management type> <option A softwood growth curve id> <option A hardwood growth curve id> <option A stocking> <option A land type> <option B softwood management type> <option B hardwood management type> <option B softwood growth curve id> <option B hardwood growth curve id> <option B stocking> <option B land type> <minimum biomass C eligibility> <maximum biomass C eligibility> <minimum merchantable C eligibility> <maximum merchantable C eligibility> <minimum softwood merchantable C eligibility> <maximum softwood merchantable C eligibility> <minimum hardwood merchantable C eligibility> <maximum hardwood merchantable C eligibility> <minimum softwood maturity eligibility> <maximum softwood maturity eligibility> <minimum hardwood maturity eligibility> <maximum hardwood maturity eligibility> <minimum softwood management type eligibility> <maximum softwood management type eligibility> <minimum hardwood management type eligibility> <maximum hardwood management type eligibility> <minimum softwood growth curve id eligibility> <maximum softwood growth curve id eligibility> <minimum hardwood growth curve id eligibility> <maximum hardwood growth curve id eligibility> <minimum stocking eligibility> <maximum stocking eligibility> <minimum land type eligibility> <maximum land type eligibility>

Line [n+1]: <number of actions in time step>

...

3.11. The Disturbance Sensitivity Analysis File

The optional disturbance sensitivity analysis file, distsens.fil, contains a multiplier that directly affects the proportion to disturb in a fire or insect disturbance. The multiplier was located in the configuration file, cb.cfg, of the original model.

Line 1: <fire/insect disturbance sensitivity analysis multiplier>

The default value for the multiplier is 1.0 (producing no effect on the proportion to disturb) should the file be absent.

3.12. The Spatial Unit Database Files

From the types of changes described in the previous section, it is apparent that conversion programs must be used to translate the binary data files on the PC to ASCII files that may be parsed on all machines. Such is the case with the growth curve and spatial unit database files.

Conversion of the spatial unit database files is done with the DOS utility AUTOUNIT.EXE which is dependent upon another utility called UNITCONV.EXE. After executing the program, the user is prompted as to whether he wishes to convert from binary to ASCII format or vice versa.

```
******************************************************************************
*                                                                            *
*                                                                            *
*                    AUTOMATED SPATIAL UNIT CONVERTER                        *
*                                                                            *
*                                                                            *
******************************************************************************


Choose the type of spatial unit conversion you desire:
      [1] From binary to ASCII,
   or [2] From ASCII to binary

Enter your choice:  1
```

The user is then asked to enter the spatial unit database filename prefix, suffix, and the number of spatial units to translate. The typical values used in the BASIC model feature the prefix svl, the suffix ini, and forty-two spatial units. For this example case, the database files entitled svl001.ini through to svl042.ini will be converted.

```
Spatial Unit File Prefix:  SVL
Spatial Unit File Suffix:  INI
Number of Spatial Units:  42
Converting 'SVL001.INI' from binary to ASCII file 'SVL001.INI'......
Converting 'SVL042.INI' from binary to ASCII file 'SVL042.INI'...
```

The final step of the process is to convert the ASCII files from DOS to Unix format using the utility dos2unix. This utility is extremely sensitive to the format of an ASCII spatial unit database file. Care must be taken to ensure that when translating from ASCII to binary that the database file is in the correct format, this being as shown below:

Line 1: <spatial unit id> <area>

Line 2: <softwood species type> <growth curve id> <management type> <maturity state> <years in state> <age> <total species C density> <merchantable C density> <foliage C density> <submerchantable C density> <other C density> <coarse root C density> <fine root C density>

Line 3: <hardwood species type> <growth curve id> <management type> <maturity state> <years in state> <age> <total species C density>

<merchantable C density> <foliage C density> <submerchantable C density> <other C density> <coarse root C density> <fine root C density>

Line 4: <total soil C density> <very fast soil pool C density> <fast soil pool C density> <medium soil pool C density> <slow soil pool C density> <peat pool C density>

Line 5: <land type> <productivity> <stocking type> <forest type> <site type>

State variable objects must be separated by an empty line. There must be no empty lines at the end of the database file.

The UNITCONV.EXE utility may be used to convert individual spatial unit database files. The program is interactive and simple enough to figure out how to use, so its usage will not be described in this document.

It is not necessary to have a database file for all spatial units involved in a model run. Should a file be missing for a particular spatial unit, it is assumed that the database for this spatial unit is empty.

3.13. The Growth Curve Files

Translating the growth curve files is performed with the utility AUTOGC.EXE which requires the program GCCONV.EXE to do its job. These programs function identically to their spatial unit database counterparts. An example that converts the files gc001.bin through gc042.bin from binary to ASCII format is shown below.

```
************************************************************************************
*                                                    *
*                                                    *
*              AUTOMATED GROWTH CURVE CONVERTER                           *
*                                                    *
*                                                    *
************************************************************************************

Choose the type of growth curve conversion you desire:
    [1] From binary to ASCII,
  or [2] From ASCII to binary

Enter your choice:  1

Growth Curve File Prefix:  GC
Growth Curve File Suffix:  INI
Number of Spatial Units:   42
```

```
Converting 'GC001.INI' from binary to ASCII file 'GC001.INI'...
...
Converting 'GC042.INI' from binary to ASCII file 'GC042.INI'...
```

Again, remember to use dos2unix to change from a DOS to Unix file format.

The C++ version of the Carbon Budget Model assumes a suffix of inf on all growth curve files, so it is important to rename them. For example, gc001.bin becomes gc001.inf.

The format of an ASCII growth curve file required when converting to binary is:

Line 1: <species> <growth curve id>

Line 2: <regeneration minimum C density> <regeneration maximum C density> <regeneration duration>

Line 3: <immature minimum C density> <immature maximum C density> <immature growth rate> <immature maximum proportion> <competition with softwood> <competition with hardwood>

Line 4: <mature minimum C density> <mature maximum C density> <mature duration>

Line 5: <overmature minimum proportion> <overmature loss rate>

Pairs of growth curves must be separated by empty lines. There can be no blank lines at the end of the file.

The interactive program GCCONV.EXE can be used to translate individual growth curve files.

3.14. The Growth Curve Sensitivity Analysis File

The growth curve sensitivity analysis file, gcsens.inf, contains the sensitivity analysis maximum biomass and growth multipliers. These values were previously in the configuration file, cb.cfg, of the BASIC model.

Line 1: <sensitivity analysis maximum biomass multiplier> <sensitivity analysis growth multiplier>

The file is optional; if nonexistent, the default multipliers of 1.0 (which have no effect) are used.

3.15. The Disturbance Matrices Files

The format of disturbance matrices files is unchanged. Such files are indicated by their default prefix spu, three-digit spatial unit id, and the suffix dsm. Thus, the matrices file for spatial unit eleven would be entitled spu011.dsm.

Each matrix in a disturbance matrices file (which contains a set of such matrices) takes the following format:

Line 1: <disturbance type>

Lines 2-18: <softwood merchantable sink proportion> <softwood foliage sink proportion> <softwood other sink proportion> <softwood submerchantable sink proportion> <softwood coarse root sink proportion> <softwood fine root sink proportion> <hardwood merchantable sink proportion> <hardwood foliage sink proportion> <hardwood other sink proportion> <hardwood submerchantable sink proportion> <hardwood coarse root sink proportion> <hardwood fine root sink proportion> <very fast soil pool sink proportion> <fast soil pool sink proportion> <medium soil pool sink proportion> <slow soil pool sink proportion> <carbon dioxide sink proportion> <methane sink proportion> <carbon monoxide sink proportion> <products sink proportion>

Each line from two through eighteen represents a carbon source. These sources are, in order:

softwood merchantable, softwood foliage, softwood other, softwood submerchantable, softwood coarse root, softwood fine root, hardwood merchantable, hardwood foliage, hardwood other, hardwood submerchantable, hardwood coarse root, hardwood fine root, very fast soil pool, fast soil pool, medium soil pool, slow soil pool, and peat pool.

If no disturbance matrix file exists for a particular spatial unit, it is assumed that the unit has no matrices (and, as a consequence, must never be affected by a disturbance.)

3.16. The Merge Suitcase File

The purpose of the merge suitcase file, suitcase.lst, is to specify the implementation of the future database hierarchy which helps speed up the process of merging state variable objects.

Line 1: <merge flag>

Line 2: <biased merging flag>

Line 3: <pre-insertion of state variable objects from current into future database>

Line 4: <allow negative differences between state variable objects as candidates for merging>

Line 5: <maximum number of merge candidates to search for>

Line 6: <number of merge field parameters>

Line 7-n: <category string> <subcategory string> <field string>

Line [n+1]: <number of merge field tolerances>

Line [n+2]-m: <category string> <subcategory string> <field string> <lower tolerance> <upper tolerance>

Line [m+1]: <number of merge field parameters in future database hierarchy>

Line [m+2]: <key category string> <key subcategory string> <key field string> <key lower tolerance> <key upper tolerance>

Comments in the file are indicated by a leading pound symbol '#'. Blank lines are not allowed.

The merge suitcase file is an exception to the rule that all input files should reside in the input directory. Because the future database hierarchy is constructed before any data is read, suitcase.lst is input before loading the input, temporary, and output paths.

An example of a merge suitcase file follows:

```
# File:  suitcase.lst
#
# This file contains the list of all parameters and tolerances
# used to decide if an SVO is a candidate to be merged with
# another SVO.  Comment lines begin with a pound '#' character.
# There can be no blank lines--the parser is confused by them.
#
# We have formed the list from the parameters and tolerances
# used in FUNCTION MergeRecord in SVLSUBS.BAS of the original
# CBM.  The tolerance ranges are from the merge constants in the
# file CB.CFG.
#
# The first field in the suitcase file is a flag reflecting
# whether we want merging of SVO's to occur.  A value of 0
# is no, any other integer infers yes.
1
#
# The second field is a flag indicating whether biased merging
# should take place.  By biased merging, I mean that two SVO's
# that were in the current database should never be merged
# together in the future database.  This is the method by which
# the original BASIC model functioned.  A value of 0 is no--
# all SVO's are candidates to be merged with all other SVO's;
# any other integer is yes, in which case biased merging is used.
0
#
# This next field flag reflects whether the original SVO's in the
# current database should be added before or after all disturbances
# take place.  A value of 0 reflects a post-disturbance insertion.
# A non-zero value infers a pre-disturbance insertion, as is done
# by the BASIC model.
0
#
# The fourth field is again a flag.  This one indicates the way in
# which the floating-point number difference between two SVO's
# should be interpreted.  The original BASIC model rejected merging
```

```
# two SVO's that had a negative difference.  This seems to be an
# odd mechanism that was altered in the new code.  Now merging
# occurs between two SVO's with a difference closest to 0.0--
# negative differences are also considered.  To ignore merging
# SVO's with negative differences, use a flag value of 0.  To
# allow negative differences, a non-zero flag must be used.
1
#
# The next field is the maximum number of merge candidates that
# may be discovered before the search algorithm quits with its
# best merge candidate.  A negative value is equivalent to
# infinity.
1000
#
# The number of value parameters that must be matched exactly
# if an SVO is to be a merge candidate:
7
#
# The list a value parameters:
species     softwood maturityState
species     hardwood maturityState
species     softwood management
species     hardwood management
classifiers -        stocking
classifiers -        land
species     hardwood growthCurve
#
# The number of tolerances (i.e. ranges) that the SVO to be merged
# must fall within for a merge candidate:
5
#
# The list of tolerances:
species     softwood age                   1000.0 1000.0
species     softwood totalBiomassCarbon    1000.0 1000.0
species     hardwood totalBiomassCarbon    1000.0 1000.0
soil        -        totalSoilCarbon       1000.0 1000.0
-           -        totalEcosystemCarbon  1000.0 1000.0
#
# The number of levels (n) in the merge parameter hierarchy.  In
# other words, the first n of the above parameters are used in forming the
# hierarchy:
```

```
3
#
# The tolerance used to compare SVO's in the future forest
# binary tree.  It is important that the value used is not
# affected during a merge; is it is, the binary tree will become
# invalid as the merged node's key value has been altered and
# this the node is in the wrong position in the tree.  This
# means that total ecosystem carbon CANNOT be used to order the
# tree.
species     softwood growthCurve          0.0    0.0
```

To mimic the behaviour of the BASIC model as closely as possible, the following suitcase file should be used:

```
# File:  suitcase.lst
#
# Merging is active:
1
#
# Biased merging should be used:
1
#
# Do pre-insertion of SVO's in the current to future database before
# disturbances:
1
#
# Allow negative differences between SVO's qualify as merge candidates.
# (This assumes we are using the BASIC model with this bug fixed.):
1
#
# The maximum number of merge candidates that may be discovered during
# insertion of a new SVO:
1000
#
# There are eight value parameters that must be matched exactly for an SVO to
# be a candidate for merging with another SVO:
8
#
# The list a value parameters:
species     softwood maturityState
species     hardwood maturityState
```

```
species      softwood management
species      hardwood management
classifiers  -        stocking
classifiers  -        land
species      softwood growthCurve
species      hardwood growthCurve
#
# The number of tolerances (i.e. ranges) that the SVO to be merged
# must fall within for a merge candidate:
5
#
# The list of tolerances:
species      softwood age                   1000.0 1000.0
species      softwood totalBiomassCarbon    1000.0 1000.0
species      hardwood totalBiomassCarbon    1000.0 1000.0
soil         -        totalSoilCarbon       1000.0 1000.0
-            -        totalEcosystemCarbon  1000.0 1000.0
#
# The number of levels (n) in the future database parameter hierarchy:
0
#
# The key tolerance used to compare SVO's in the future database binary tree:
-            -        none                     0.0    0.0
```

4. Running the Model

Having compiled the code and set up the input files, the model is ready to be executed. This is a simple matter--enter

```
%cbm
```

at the UNIX prompt.

The Object-Oriented Carbon Budget Model is fairly good at catching and reporting errors in input files. If any bad data is discovered, a descriptive error or warning is displayed. If the problem is not deemed severe, as is the case with warnings, the model continues to execute (often using default values for information that was not correctly input). If the error is significant, however, the program terminates.

During the course of the run, the model will keep the user up-to-date as to its progress. Descriptions include an indication of the database currently being loaded, the spatial unit being grown, the current pass (and within the pass, the spatial unit) to which a disturbance is being applied, summaries of the results of a disturbance regime, and the database currently being archived to a file.

4.1. The Resulting Output Files

4.1.1. The Carbon Flux File

The carbon flux file, fluxind.out, contains the change in carbon due to growth, soil dynamics, and most importantly, disturbances. The file remains equivalent to its BASIC counterpart for the most part. The only minor difference is that the values are floating-point numbers rather than being rounded to integers as in the BASIC Carbon Budget Model carbon flux file. This change should have no effect when running, say, the Carbon Tables utility C-TABLES.EXE, which expects floating-point number fields anyway.

Line n: <time step number> <disturbance type of pass> <spatial unit id> <carbon dioxide production> <methane production> <carbon monoxide production> <carbon dioxide biomass emissions> <methane biomass emissions> <carbon monoxide biomass emissions> <carbon dioxide soil emissions> <methane soil emissions> <carbon monoxide soil emissions> <softwood forest products> <hardwood forest products> <soil products> <change in biomass carbon> <change in soil carbon> <transfer of carbon from biomass to soil>

There are sufficient lines for all time steps, disturbance passes, and active spatial units present in the simulation.

4.1.2. The Pool Carbon File

The total carbon in the various species components and soil pools is described in the pool carbon file poolind.out. Similar to the carbon flux file, the fields are in floating-point notation rather than integers, but again this will not pose a problem.

Line n: <time step number> <spatial unit id> <softwood merchantable carbon> <softwood foliage carbon> <softwood other carbon> <softwood submerchantable carbon> <softwood coarse root carbon> <softwood fine root carbon> <hardwood merchantable carbon> <hardwood foliage carbon> <hardwood other carbon> <hardwood submerchantable carbon> <hardwood coarse root carbon> <hardwood fine root carbon> <very fast soil pool carbon> <fast soil pool carbon> <medium soil pool carbon> <slow soil pool carbon> <peat pool carbon>

There is an entry for every active spatial unit for every time step of the run.

4.1.3. The Age Indicators File

The age indicators file, ageind.out, gives a summary of the area, biomass carbon, soil carbon, and the average age of state variable objects for the various age groups of a spatial unit. The only minor difference between the object-oriented and BASIC model versions of this file is that the summary fields are floating-point numbers rather than integers.

Line n: <time step number> <spatial unit id> <age classification> <area> <biomass carbon> <soil carbon> <average age>

There is an entry for each age classification for every active spatial unit in each time step of the simulation. The possible age categories are *unclassified, 0 to 19 years, 20 to 39 years, 40 to 59 years, 60 to 79 years, 80 to 99 years, 100 to 119 years, 120 to 139 years, 140 through 159 years, 160 to 179 years, 180 to 199 years*, and *200 or more years*.

4.1.4. The Disturbances by Group Indicator File

The total area affected and the carbon products created during each disturbance pass for each group of each time step is archived to the disturbances by group file distindg.out.

Line n: <time step number> <disturbance type of pass> <disturbance group> <area> <products carbon>

4.1.5. The Disturbances by Spatial Unit Indicator File

The disturbances by spatial unit indicator file, distinds.out, is similar to its disturbances by group counterpart except that the area affected and the carbon products made during each disturbance pass is classified by spatial unit. Each time step in the run is represented.

Line n: <time step number> <disturbance type of pass> <spatial unit> <area> <products carbon>

4.1.6. The Ecocheck File

The ecocheck file, ecocheck.out, is intended to provide a convenient archive of the effects of growth and soil dynamics on a state variable object level. As each such object is grown and its soil pools updated, a new entry is written to the file indicating the object's new state and the transfers of carbon made.

Line n: <year> <spatial unit id> <area of SVO> <total biomass C density> <hardwood species id> <hardwood growth curve id> <hardwood management type> <hardwood maturity state> <hardwood years in state> <hardwood age> <hardwood biomass C density> <hardwood merchantable C density> <hardwood foliage C density> <hardwood submerchantable C density> <hardwood other C density> <hardwood coarse root C density> <hardwood fine root C density> <softwood species id> <softwood growth curve id> <softwood management type> <softwood maturity state> <softwood years in state> <softwood age> <softwood biomass C density> <softwood merchantable C density> <softwood foliage C density> <softwood submerchantable C density> <softwood other C density> <softwood coarse root C density> <softwood fine root C density> <total

soil C density> <very fast soil pool C density> <fast soil pool C density> <medium soil pool C density> <slow soil pool C density> <peat pool C density> <yearly fine root litter input> <yearly coarse root litter input> <yearly foliage litter input> <yearly other litter input> <yearly merchantable litter input> <yearly carbon transfer to air from very fast soil pool> <yearly carbon transfer to air from fast soil pool> <yearly carbon transfer to air from medium soil pool> <yearly carbon transfer to air from slow soil pool> <yearly carbon transfer to air from peat pool> <yearly carbon transfer from very fast to slow soil pool> <yearly carbon transfer from fast to slow soil pool> <yearly carbon transfer from medium to slow soil pool> <yearly carbon transfer from slow to slow pool (unused)> <yearly change in hardwood merchantable C density> <yearly change in hardwood foliage C density> <yearly change in hardwood other C density> <yearly change in hardwood submerchantable C density> <yearly change in hardwood coarse root C density> <yearly change in hardwood fine root C density> <yearly change in softwood merchantable C density> <yearly change in softwood foliage C density> <yearly change in softwood other C density> <yearly change in softwood submerchantable C density> <yearly change in softwood coarse root C density> <yearly change in softwood fine root C density> <yearly change including litter input to fine root C density>

It is important to point out that the format of this file differs from the BASIC ecocheck file, specifically in the order of species and soil carbon density fields.

4.1.7. The Undisturbed Area File

The undisturbed area file, nodist.out, indicates the amount of area designated for disturbance but wasn't due to a lack of eligible area. The output is tallied by time step, disturbance type, and group.

Line n: <time step> <disturbance type id> <disturbance group id> <undisturbed area>

4.1.8. The Spatial Unit Archive Files

At the conclusion of a run, the current state of the model as reflected by the spatial unit databases are output to the files svl*xxx*.dat. The BASIC version uses a binary format while the object-oriented model outputs the spatial units in ASCII with the format given in **The Spatial Unit Database Files** section.

5. Sorting the Spatial Unit Databases

An additional utility entitled sort takes a spatial unit database file and sorts it according to the parameters and tolerances given in the merge suitcase file. The program accepts one argument--the name of the file to sort.

%./sort <spatial unit database filename>

The main reason for creating such a utility is to sort the resulting database of the BASIC model using the same keys as the C++ model. This allows the spatial units to be easily compared because any two SVO's should reside in similar positions in the two database files.

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1 Past and Possible Future Carbon Dynamics of Canada's Boreal Forest Ecosystems

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Abstract: Forest fires and insect outbreaks are the predominant disturbance agents in the vast boreal forest ecosystems of North America; harvesting affects a relatively small proportion of the average total area disturbed each year. In spite of protection programs, the rate of natural disturbances has fluctuated considerably in the recent past, which is almost certainly related to variations in average climate. Disturbance rate is a key factor controlling the age-class distribution of the forest: increased disturbances lead to increased proportions of younger age classes and lower average densities of carbon (C) stored in biomass, litter and soil. Hence natural disturbances are a major influence over ecosystem C dynamics in unmanaged boreal forest regions.

Simulations of the major pools and fluxes in the ecosystem C balance were used to investigate past and possible future disturbance scenarios and possible management responses on C storage in Canadian boreal ecosystems, at both regional and local scales. The results showed that until recently the entire Canadian boreal was a net sink for C, but increased disturbances in the period 1970–1990 reversed this process. Disturbance regimes will continue to affect the net C balance in the future, with the system likely to remain a net C source for several years. Management for timber production, which includes investment in protection against natural disturbances, could help overcome this effect. Harvesting is a necessary component of long-term management, because protection can only delay natural disturbances in boreal ecosystems, and the cost of C storage will otherwise increase considerably as stands age. The manufacture of long-lived wood products and fossil energy substitutes are additional possible strategies in using boreal forests to mitigate anthropogenic greenhouse gas emissions.

1.1 Introduction

Recent findings of Keeling et al. (1995) suggest that carbon exchange between the global atmosphere and the biosphere is dependent upon global climatic fluctuations due to El Niño–Southern Oscillation events and other large-scale phenomena, such as volcanic eruptions. Two important implications from their work, of particular relevance to the issue of anthropogenic greenhouse gas (GHG) emissions, are: (1) small changes in global forcings can shift the earth's ecosystems from acting as C sinks to C sources and back; and (2) these shifts occur against a background of increasing atmospheric GHG concentrations. Whatever opportunities may exist for managing terrestrial ecosystems to mitigate emissions, must take such factors into account.

Some analyses of recent global terrestrial C budgets have assumed that natural (i.e., unmanaged) forests are in steady-state, and therefore do not contribute significantly to observed changes in global C emissions; after fossil fuel combustion, the major contributions are believed to result from deforestation and other land-use changes (e.g., Houghton et al. 1983, 1987; Dixon et al. 1994). Two corollaries of this assumption are firstly that forest age-class structure, averaged over large spatial scales, remains essentially unchanged, which implies secondly that the average forest age is approximately constant (Kurz et al. 1995b). Any unmanaged forest, comprised largely of mosaics of even-aged stands, is the product of past stand-replacing disturbances, such as wildfire and insect attacks, whose frequency may vary, e.g., due to variation in climate. Significant departures in the large-scale age-class distribution from a negative exponential curve would therefore indicate historical disturbance episodes of significantly greater or lesser frequency than the long-term average. Such departures have been observed for Canadian forests (Kurz and Apps, 1993) and have led to the realisation that natural forest ecosystems can act periodically as C sinks or C sources (Kurz et al. 1995b, Kurz and Apps 1995, 1996). Hence the assumption of long-term steady-state C exchange in natural forest ecosystems should be challenged, even at the global scale (Kurz et al. 1995b). In practice, the concept of a long-term average disturbance rate may itself be misleading, because the period over which the true average could be determined is much longer than the post-1860 industrial era, during which most effects of anthropogenic emissions have been observed (Apps and Price, 1996).

In managed forests, the age-class distribution is influenced by management history as well as by disturbances. Management for timber production, which usually implies protection against natural disturbances and their replacement by harvesting, is generally aimed at manipulating the age-class distribution towards that of a normal forest (i.e., with equal areas in each age class). Changes in forestry policy, land values, timber markets and the inevitable chance occurrences of natural disturbances, however, continually prevent a smooth age-class distribution from ever existing in reality (e.g., see Maclaren, 1996). This in turn implies that even managed forests may alternate periodically between acting as C sinks and sources.

The underlying explanation for variation in the sink/source function is that C dynamics in all forest ecosystems are governed by several natural processes operating at greatly differing time scales. For example, the quantities of C residing in different dead organic matter pools (fine root residues, leaf-litter, coarse woody debris, humus, etc.) are governed by their different decay rates (subject to environmental influences), as well as by the rate of input of dead plant material (which is largely determined by average primary productivity and the stage of stand development). The C dynamics of these continuous processes contrast with those of discrete large-scale disturbances which trigger massive discontinuous transfers of C among different pools, while resetting stand development. Processes with long time constants (particularly disturbances) can thereby introduce inertia and "memory" into ecosystem structure (Kurz et al. 1995b; Apps and Price, 1996).

It is impossible to quantify human influences on the forest without first understanding the spatial and temporal dynamics controlling the natural ecosystem structure. Interpreting a forest's age-class distribution is essential to understanding its history of both disturbances and management, prior to investigating their impacts on past and possible future ecosystem C dynamics. This process can be greatly facilitated using scenario assessments performed with models such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) (e.g., Kurz et al. 1992). The main purpose of this paper is to show how natural disturbances may contribute to fluctuations in large-scale forest C budgets, by summarising selected results from our own CBM-CFS2 analyses of past, and possible future, C budgets of Canada's boreal forest and tundra ecosystems. A second objective is then to assess the consequences of current forest management techniques on these C budgets, with a view to identifying the most promising methods of managing Canadian forests to offset GHG emissions.

The circumpolar boreal (taiga) and subarctic (tundra) biomes of North America, Europe and Asia are of particular interest to the issues of global C cycling and anticipated climate change, because they harbour vast stores of organic C which have accumulated since the last glaciation (Apps et al. 1993a). On the one hand, these biomes evidently act as sinks for atmospheric CO_2. Recent studies, notably those of Tans et al. (1990) and Ciais et al. (1995), have focused attention on this role and suggest that, together with the northern temperate forests, these biomes may be the major location of the so-called "missing carbon sink". On the other hand, many high-latitude ecosystems appear particularly sensitive to climate change. Fears have been expressed that a warmer climate would cause drying out of wetlands, melting of permafrost regions, and greater incidence of forest-fires and damaging insect outbreaks, with consequent increased emissions of CO_2 and methane, and reduced net uptake of atmospheric C (Woodwell and Mackenzie 1995; Kurz et al. 1995a; Zoltai and Martikainen 1996; Stocks et al. 1996; Volney 1996). In short, anthropogenic GHG-induced climate warming may trigger a runaway feedback effect—with possibly catastrophic global consequences.

Clearly, understanding the large-scale C dynamics of the circumpolar boreal zone is of considerable relevance to the issue of managing boreal ecosystems to mitigate anthropogenic emissions of GHGs. This paper therefore assesses the effects of different plausible management strategies applied to Canada's boreal-zone forests to determine their potential for anthropogenic GHG mitigation, based on both biome- and forest- scale simulations.

Finally, we discuss how the simulation results provide evidence that climate-driven changes in natural disturbance frequency may significantly affect the sink/source role of forests in general, and that the memory inherent in the structure of many forest ecosystems may lead to irregular and sustained reversals of the large-scale C flux (Kurz et al. 1995b, Kurz and Apps 1995, 1996). The implications of this will then be discussed in the context of current and anticipated future GHG emissions, and in the light of possible climate change.

1.2 Model Description

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) is a large-scale, object-oriented simulator of C dynamics in natural and managed forest ecosystems. Originally developed to assess the C budget of Canadian forests (Apps and Kurz 1991; Kurz et al., 1992; Kurz and Apps 1994), it has since been applied at the regional scale (Apps and Kurz 1993; Apps et al. 1993; Kurz and Apps 1993, 1994, 1996; Kurz et al. 1995b), and at the individual forest scale (Price et al. 1994, 1996). The model is described in detail in several publications op. cit., so only a very brief description of relevant aspects will be given here. CBM-CFS2 uses data derived from forest inventories, ecosystem classifications, soil surveys and other government and industry statistics, to estimate the C content of four distinct pools: biomass, soils, peatlands and wood products (including material dumped in landfills). Similar approaches have recently been adopted by Turner et al. (1995) to construct a forest sector C budget for the U.S., and by Karjalainen et al. (this volume) for Finland. To improve computational efficiency, however, CBM-CFS2 is not based on an explicit spatial representation (e.g., as could be obtained from a geographic information system): instead the smallest spatial units are delineated by the intersection of large-scale administrative and ecological boundaries. For this reason, CBM-CFS2 can be adapted for use at widely differing spatial scales, as outlined below.

1.2.1 Biomass Production and Soil Decomposition

Individual forested ecoclimatic regions, as identified in national and provincial ecosystem classifications (Ecoregions Working Group 1989), are each represented within CBM-CFS2 by sets of ecosystem types. Each ecosystem type possesses a pair of characteristic biomass growth curves (for softwood and hardwood species) as well as other attributes such as site class and stocking (Kurz and Apps 1994).

The model also estimates annual litterfall and tree mortality, including that caused by disturbances. Some C is released to the atmosphere, but the remainder is assumed to be transferred to the soil, via intermediate litter pools. The C contained in litter and coarse woody debris is allocated among three pools, each with a characteristic decomposition rate. During decomposition, much of the C contained in these pools is released as CO_2, while the residues are transferred to a fourth slow soil humus pool (Kurz and Apps 1994). It should be noted that the analyses presented here do not account for the effects of possible changes in temperature or precipitation regimes on growth or decomposition.

1.2.2 Disturbances

During any disturbance event, a significant portion of the C stored in forest vegetation is invariably transferred from the live biomass pool to one or more dead organic matter pools. Other portions may be released to the atmosphere (e.g., fire, insect infestation) or, transferred to wood products (in the case of harvesting, which includes salvage of material damaged by other disturbance agents). In CBM-CFS2 therefore, each type of disturbance is identified by a characteristic set of coefficients corresponding to the proportions of available biomass C transferred to atmosphere, soil pools and products. Such information is stored in so-called "disturbance matrices" which are applied to eligible forest ecosystem types (defined by area, available biomass, age and other attributes) whenever the effects of large-scale disturbances are to be assessed (Kurz et al. 1992, 1995b). Disturbances are applied to prescribed areas of eligible ecosystem types, in all age classes. Newly disturbed areas are reset to zero age, so that changes in age-class structure may be simulated. Disturbance effects are averaged over a user-determined timestep, typically five years, which also sets the model's reporting interval.

1.2.3 Forest Product Sector

Harvested forest biomass C is converted to wood products, with product-specific efficiencies and C losses to the atmosphere and to landfills. The C contained in the resulting wood products is subsequently released to the atmosphere through oxidation as they decay in buildings and landfills, or are burned as waste or for energy. This process is represented by a set of decay functions for different product categories (Kurz et al. 1992).

1.2.4 Model Operation

The model maintains a database where each record represents the total area within a spatial unit of a given ecosystem type in a given age class. Every timestep, the model uses the data in each record to: (1) estimate forest growth and decomposition; (2) update biomass and soil C densities; (3) apply disturbances and calculate the resultant transfers among pools; and (4) recalculate the inventories of total C. When summed over each spatial unit, the changes in total C content are used to report net C fluxes between biomass, atmosphere, soils and wood products.

1.3 Simulations

CBM-CFS2 was used to perform a retrospective C budget assessment for Canadian boreal and subarctic ecosystems for the period 1920–1989 (Kurz and Apps 1996) and a 50-year projective assessment (1990–2040) (Kurz and Apps, 1995). For these regional simulations, 303 Mha of boreal and subarctic forested ecosystems (about 75% of Canada's total forest area) were grouped into 18 spatial units, defined by the intersection of the Provinces and Territories with the Canadian ecoclimatic zones (Kurz et al. 1992).

In a second C budget study, CBM-CFS2 was applied at the scale of an individual forest management unit to assess the impacts of management for the period 1950–2180 (Price et al. 1994, 1996). The 1.2 Mha Foothills Forest is one of ten demonstration forests, established by the Canadian federal government in a program to develop sustainable forest management at sites representative of the major forest ecoregions of Canada. Foothills Forest is located predominantly in the boreal ecoregions of central Alberta, east of the Rocky Mountains (Jasper National Park). The forest management agreement (FMA) area covers approximately 800,000 ha, and is operated by Weldwood of Canada Ltd., primarily for timber production. All wood products derived from the Foothills Forest are processed in local mills.

1.3.1 Growth Curve Parameterization

For the regional scale assessments, the growth curves were parameterized using data from the national biomass inventory (Bonnor 1985). Net primary production (which removes C from the atmosphere) is estimated in yearly timesteps from the growth curves. For the Foothills FMA area, Weldwood's merchantable volume yield curves (Weldwood 1992) were used to parameterize the biomass growth curves (Price et al. 1996), using empirical equations of Singh (1984) for central Canadian species (with which merchantable volume data were scaled to aboveground biomass). In both cases, belowground biomass was estimated using methods and equations outlined in Kurz et al. (1996).

1.3.2 Disturbance and Management Scenarios

Regional-Scale Simulations: Databases on harvesting rates, wildfires, insect outbreaks, and planting programs were compiled for each spatial unit, extending back to 1920, from a variety of government sources. Where necessary, data gaps were filled by extrapolation using data from adjacent spatial units or time periods as proxies. Figure 1 summarises disturbance rates for the period 1920–1989 and those assumed for the projective runs. Historically, total disturbances in the boreal forest averaged 1.7 Mha yr^{-1} for the period 1920–1969, but increased markedly to 3.9 Mha yr^{-1} for the period 1970–1989. Fires and insects are the major disturbance agents, although harvesting levels have increased steadily throughout the 70-year period.

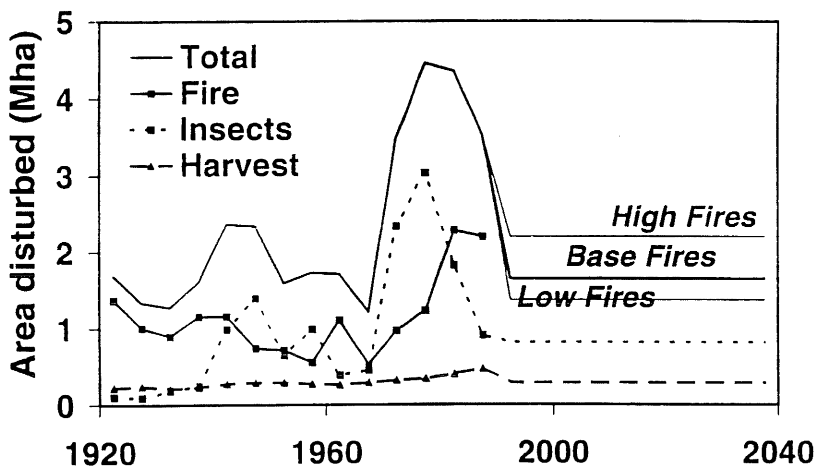

Fig. 1. Observed five-year averages of areas annually disturbed in the Canadian boreal and subarctic ecoclimatic provinces for the period 1920-1989 and assumed disturbance regimes for the projective Base Run and Low Fire and High Fire scenarios for the period 1990-2040. The area disturbed by fires in each of the three fire scenarios is the *difference* between the "Insects" and the "Fire" plots. (Redrawn from Kurz and Apps 1995.)

For the retrospective simulations, data on forest age-class structure in 1920 were needed to initialise CBM-CFS2, but such data do not exist. Instead, age-class distributions were reconstructed for 1920, using an iterative modelling approach explained in detail by Kurz et al. (1995a). Briefly, the disturbance history databases and biomass growth curves were applied to an estimate of the 1920 forest structure, using a rule-based model developed for the purpose. It was assumed that total forest area, and its distribution among ecosystem types, in 1920 were unchanged in 1970. After running the model for 50 years, the results were compared to the known 1970 age-class structure derived from Bonnor (1985) and Forestry Canada (1988). The discrepancies were used to adjust the 1920 age-class structure and the process repeated until acceptable agreement was obtained. Sensitivity testing showed it was not possible to obtain greatly differing initial forest structures using rules that also met valid ecological constraints.

For the projective scenarios, it was assumed that annual disturbance rates would remain constant, relative to a baseline of actual rates during the last five years (1985–89). Average harvest rates have decreased recently (Canadian Council of Forest Ministers, 1994), so harvesting and regeneration rates were set to 90% of the baseline. Insect-induced stand mortality was assumed to remain at baseline. Three fire scenarios were considered: the base projection recognised that during the decade 1980–89, average annual temperatures (Gullett and Skinner, 1992), and areas lost to fire (Figure 1), were the highest since records began in Canada—presumably not mere coincidence. For the subsequent period 1990–1993, areas burned were about half the 1980s' rate (Canadian Council of Forest Ministers, 1994; Canadian Forest Service, unpublished data). Hence, the base fire projection assumed an annual area burned of 60% of the average for 1985–1989 (or 143% of that for 1920–1969). Further details of these scenarios are given in Table 1.1. It should be emphasised that the levels of disturbance chosen for the projective scenarios were representative of the past history; they should not be considered as predictions of future disturbance regimes.

Forest-Scale Simulations: For the Foothills Forest analysis, local disturbance records were available for the period 1954 onward. The earlier fire history of the area has also been reported by van Wagner (1978) and others. Fire suppression has been practised since *ca.* 1915 and relatively few major fires have occurred since that time. On the other hand, commercial logging of old-growth stands and their replacement by managed stands began in 1954 and has continued since then. To assess the impacts of this human activity on the natural disturbance regime and its consequences for C dynamics, three scenarios were investigated, summarised in Table 1.2.

Inventory data for the Foothills Forest were available only for 1988, but, like the regional simulations, it was necessary to initialise CBM-CFS2 with a reconstructed age-class distribution, in this case for 1958. Because the area involved was much smaller (and considered to lie in a single ecoregion), and the disturbance history during the intervening period was well documented (mainly

Table 1.1. Summary of assumptions for six scenarios of forest dynamics of Canadian boreal forests, for 50 years commencing in 1990 (from Kurz and Apps 1995). The estimates of areas planted are totals over the 50-year period.

Scenario	Assumptions	Area planted [Mha]
Base Run	Harvest and planting at 90% of 1985–89 levels; fire at 60% of 1985–89 levels; insect-induced mortality at 100% of 1985–89 levels.	4.6
Low Fire	Fire at 50% of Base Run	4.6
High Fire	Fire at 200% of Base Run	4.6
Plant All	All disturbed areas are planted	132.0
Conversion	Non-stocked areas converted to high yield stands at 1% of eligible area each year	58.2
Selective Conversion	Non-stocked areas with less than 2 Mg C ha-1 converted to high yield stands at 5% of eligible area each year	51.8

Table 1.2. Summary of assumptions for three scenarios of C dynamics of the Foothills Forest, a boreal forest management unit in Alberta, Canada. All scenarios are assumed to commence in 1958. (From Price et al. 1996).

Scenario	Assumptions
Unmanaged	No harvesting and no management. In particular fires allowed to occur at an average return interval of 50 years (similar to that believed to occur prior to *ca.* 1915).
Harvesting Only	Harvesting and stand regeneration at historical rate 1958–1988, and following planned maximum sustainable yield (MSY) for 1989–2188. Complete suppression of fires and other natural disturbance agents.
Harvesting-plus-Silviculture	As for "Harvesting Only", but also assuming 50% gain in biomass productivity in regenerated stands due to silvicultural treatments.

harvesting), this was tackled using a simpler approach. It was assumed that only stocked stands greater than 60 years old would be harvested, and that the areas growing according to each Weldwood yield curve were harvested in proportion to their total area in the forest in 1958.

The "Harvesting Only" scenario of Table 1.2 assumes that biomass productivity will not change significantly as old-growth stands (predominantly of lodgepole pine, *Pinus contorta* Dougl.) are gradually replaced by younger managed stands (a process scheduled over a 100-year period). In reality, however, stand manipulations and other silvicultural treatments are practised with the intention of reducing competition and increasing merchantable volume production. Although subject to considerable debate, there is some evidence that pre-commercial thinning of dense lodgepole pine stands, particularly those that regenerate naturally following fire, leads to increased aboveground biomass production. The "Harvesting-plus-Silviculture" scenario is therefore a best-case scenario which assumes that increases in merchantable volume productivity resulting from silvicultural treatments result in proportional increases in biomass productivity. The "Harvesting Only" scenario is the corresponding worst case scenario.

1.3.3 Wood Products: Manufacturing and Disposal

Forest-Scale Simulations: The processing of timber harvested in the Foothills Forest FMA area is well-documented in the Forest Management Plan (Weldwood 1992). Approximately 75% of energy needs is derived from wood waste and spent pulp liquor, and a further study is underway to account for all GHG emissions related to fossil energy consumed, both by the mills and by vehicles and equipment used in management and harvesting operations.

Statistics on timber harvesting and the production of lumber and pulp from the mills were compiled, and used to construct annual balance sheets to track the flows of biomass C transferred to the soil pool during harvesting, and to the products pool, dumped as waste, or lost to the atmosphere. It was found that even the worst-case harvesting scenario could supply enough wood to maintain planned production rates for the period of interest (Price et al. 1996).

1.4 Results

1.4.1 Effects of Disturbances on Age-Class Structure and C Dynamics

Regional-Scale Simulations: Figure 2 shows that for Canada's boreal and tundra ecosystems, climate-related fluctuations in the disturbance rate (i.e., average area disturbed per year), resulted in changes to average forest age as well as to age-class structure. The reconstructed 1920 age-class distribution yielded an average age of 60.9 years (Figure 2a), which increased to 82.5 years by the time of the 1970 inventory (Figure 2b). This increase implies that the average total disturbance rate (1.7 Mha yr^{-1}) was lower in the period 1920–1969 than prior to 1920. Figure 1 shows that during 1970–1989, the natural disturbance rate (i.e., fire and insect-induced mortality), approximately doubled (to 3.9 Mha yr^{-1}). This caused a greater transfer of area to the youngest age classes, resulting in average forest age decreasing to 76.4 years by 1990 (Figure 2c).

In the period 1920–1989, total C storage in Canadian boreal ecosystems increased by approximately 8.3 Pg C, mainly in soils, averaging about 118 Tg C yr^{-1}. For the first 60 years, they acted as a net sink, (i.e., net ecosystem productivity, NEP, was positive) averaging 147 Tg C yr^{-1} (Figure 3). For the final 10 years, following the onset of a greatly increased disturbance rate in the early 1970s, these ecosystems became a net C source (NEP negative), averaging -57 Tg C yr^{-1}.

During 1920–1969, the net transfer of C from biomass to soil pools averaged about 100 Tg C yr^{-1} (Figure 3), of which 57 Tg C yr^{-1} was due to disturbances. The increased disturbance rate in 1970–1989 caused C transfers due to disturbance to increase to 156 Tg C yr^{-1}. The switch from C sink to C source *ca.* 1980–1985 can therefore be attributed to the interaction of three factors: (a) increased losses of C resulting directly from increased disturbances; (b) consequent greater accumulations of decaying material in litter and soils; and (c) a higher proportion of young and regenerating stands of lower net ecosystem productivity. Because it will take some time for the decomposable pools to disappear (i.e., their decay time constants are of the order of decades), and for the large area of newly regenerated young stands to reach maximum productivity, the net C source effect is likely to continue for some time.

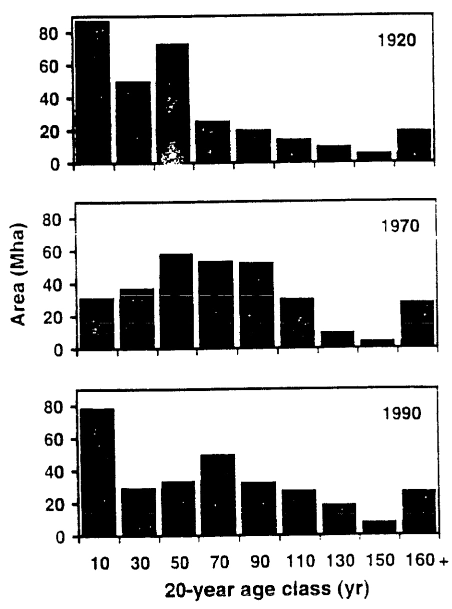

Fig. 2. Changes in forest age-class structure for Canadian boreal and subarctic forest ecosystems in 1920, 1970 and 1990. The data for 1920 were reconstructed from the 1970 inventory using the record of known disturbances and an iterative modelling approach. (Redrawn from Kurz and Apps 1996.)

The latter assertion is supported by the projection of annual net changes in ecosystem C pools, (Figure 3, right-hand side). It is important to emphasise that this projection assumes no change in current average climate and land management practises, and a constant annual disturbance rate around 2.4 Mha yr^{-1} (i.e., lower than the average during 1970–89, but higher than during 1920–69). Under these conditions, Canadian boreal ecosystems are projected to remain a C source until *ca.* 2010.

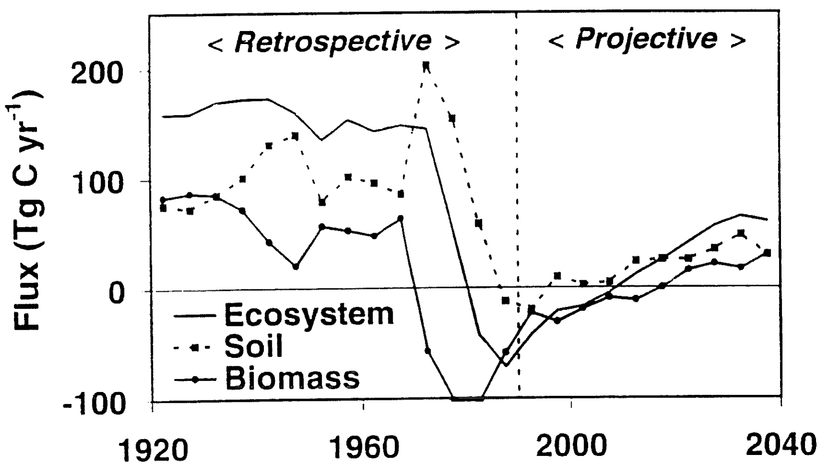

Fig. 3. Annual net changes in biomass, soil and total ecosystem C in Canadian boreal and subarctic forest ecosystems for the retrospective period (1920–1989) and for the projective Base Run (assuming fires at 60% of the rate during 1985–89). Positive flux indicates increased storage in the indicated component. (Redrawn from Kurz and Apps 1995.)

Forest-Scale Simulations: Figure 4 shows the average changes in ecosystem C storage for the Foothills Forest FMA area that would be expected to occur over the period 1958–2188, if only a constant natural disturbance regime (average return interval of 50 years) had prevailed. Biomass C storage is steadily reduced for the period 1958–2050 (approximately -1.5 Tg C yr^{-1}), because it had accumulated during a period of reduced disturbances. The decomposable material transferred to the soil pools undergoes a transient increase for the first 30 years, before it too begins to decrease. The combination of these trends causes the ecosystem to shift from a C sink to a C source *ca.* 1980. Total C storage (i.e., of the ecosystem including wood products) tends toward stability over the next 150 years, although continuing to decline slightly. Part of the explanation for this is an artefact due to the assumption of a constant average disturbance regime. In reality, storage will respond to fluctuations in disturbance rate. The general decrease in storage however, demonstrates the memory in the system: the effects of an initial increase in biomass over a period of less than 100 years, during which fire suppression efforts were in effect, are still detectable 230 years later (hysteresis).

It should be emphasised that the low disturbance rate observed in reality for the Foothills Forest area may be the consequence of successful fire control measures since 1915—or it may rather be due to the same climate-related factors that contributed to lower than average disturbance rates across the entire Canadian boreal zone, at least for the period prior to 1970. Examination of the age-class distribution of the Foothills Forest (see Price et al. 1996, Figure 23.1), shows that there were extensive areas disturbed in the period 1885–1905, compared to the reconstructed 1920 regional age-class structure (Figure 2) which suggests that disturbance rates were higher than normal in the period *ca.* 1860–1880. Although the periods of high disturbance rates in these two studies do not actually overlap, the general interpretation is unaffected.

1.4.2 Effects of Management on Boreal Ecosystem C Dynamics

Forest-Scale Simulations: The impacts of current management practices in the Foothills Forest are shown in Figure 5. Both scenarios assume complete suppression of natural disturbances from 1958, but "Harvesting Only" (Figure 5a) assumes no improvements in biomass productivity following harvesting, whereas the "Harvesting-plus-Silviculture" (Figure 5b) assumes an average increase of about 50% due to silvicultural treatments. The effects of management are clearly to increase total ecosystem C storage relative to the unmanaged projection. With harvesting only, a net C sink is projected until *ca.* 2090. The switch to a source is caused by biomass decreasing from *ca.* 2020 leading to reduced inputs to the soil pool. The decrease in biomass results from unsustainable timber volume removal; conversely when silvicultural effects are added, the increased biomass productivity exceeds anticipated harvesting, and allows both biomass and soil C to increase steadily for the entire period. The increases in the soil C pool are attributable to the steady input of litter from harvesting and natural mortality when natural disturbances are suppressed, combined with the low decay rate, which prevents equilibrium from being reached during the simulated period. Products account for a relatively small proportion of total C storage, primarily because of the proportion of pulp products.

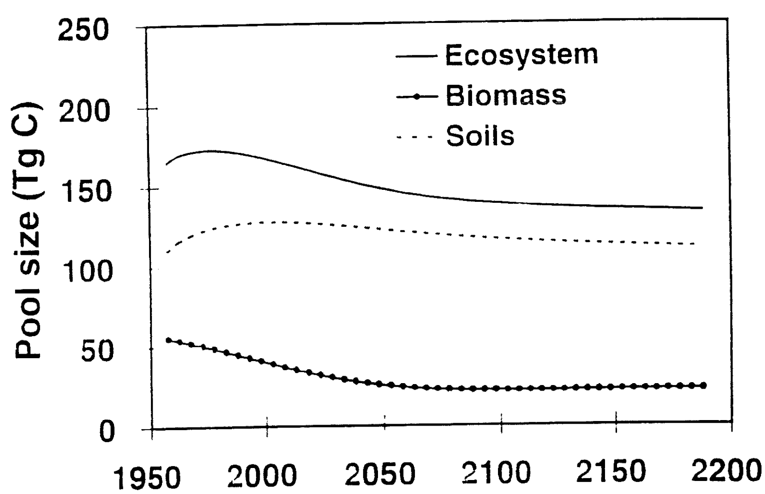

Fig. 4. Changes in average accumulations of biomass, soil and total ecosystem C for the Foothills Forest management agreement area expected to occur over the period 1958–2188 in the absence of human intervention, and assuming a constant natural disturbance interval of 50 years. (Redrawn from Price et al. 1996.)

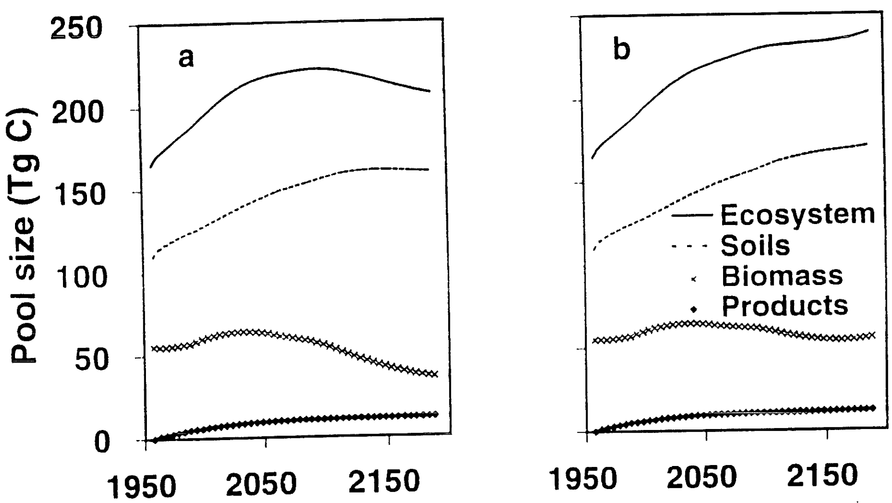

Fig. 5. Worst and best case estimates of changes in average accumulations of biomass, soil, wood products and total C for the Foothills Forest management agreement area expected to occur over the period 1958–2188 under past and anticipated future management and harvesting regimes. (a) Harvesting Only scenario assumes complete suppression of natural disturbances and planned harvesting with no increases in stand productivity following harvesting. (b) Harvesting-plus-Silviculture scenario also assumes approximate 50% increase in average productivity of pine stands following harvesting. (Redrawn from Price et al. 1996.)

These results for the specific case of a forest management operation in western Alberta indicate that it is possible for management activities to increase C sequestration in boreal forest ecosystems. There are, however, some important caveats which must be noted before considering what the larger scale implications might be. Firstly, and most importantly, the net increase in ecosystem C under management is due largely to increasing the average age of the forest, because the managed rotation age is significantly greater than the assumed 50-year natural disturbance interval. It should be emphasised that this disturbance interval is rather shorter than the average for most Canadian boreal stands, which is probably of the order of 100 years. For other forest ecosystems, such as the long-lived forests of the Pacific Northwest, the natural disturbance interval is considerably greater than the managed rotation length, which causes managed forests to store considerably less C on average (e.g., Harmon et al. 1990).

Secondly, it has been assumed that there is no systematic change in climate and other environmental factors which might affect ecosystem behaviour. Clearly, there is a significant possibility that climate warming will occur in the same time-frame as these projections, which would be likely to increase the probability of fire and insect attacks, as well as increasing respiration rates, and possibly, adversely affecting biomass productivity. Soil C, in particular, increases under both managed scenarios because fire suppression reduces C transfers from soil to atmosphere, and increases those from biomass to soil. Because total soil C accumulation is very sensitive to the decomposition rate, ecosystem C storage would be very sensitive to climatic variation. Related studies have indicated that climate warming may cause net decreases in total boreal ecosystem C storage, because decomposition losses from soils exceed any gains due to increased bioproductivity (Price et al. unpublished). On the other hand, any systematic change in climate would be expected to affect both managed and unmanaged scenarios. This could reduce total ecosystem C storage, but some gains from management would be expected to remain.

Thirdly, control of fire and insect disturbances is unlikely to be completely effective in any case—although it should be recognised that protection of forest managed for timber production is likely to be more successful than protection of unharvested forest, because harvesting also reduces fuel accumulation (and hence C losses). Reductions in fuel accumulation due to harvesting have also been observed for managed forests in Scandinavia (e.g., Kellomäki and Karjalainen 1996). Harvesting areas can be managed to reduce the spread of big fires, while controlled slash-burning in periods of low fire danger can greatly reduce the quantity of fine fuels (which would otherwise decompose rapidly if not burned). Furthermore, managed forests tend to be nearer population centres and have better developed road systems. It is partly for the latter reasons that fire control efforts in the southern Canadian boreal regions have reduced the average disturbance rate, contributing to a shift in forest age-class structure toward older age classes (Stocks et al. 1996; Blais 1983).

Regional-Scale Simulations: Alternative management scenarios applied to the boreal region (from Table 1.1) are compared in Figure 6. Reducing the natural disturbance rate ("Low Fire" scenario) would significantly advance the switch from a C source to a C sink, whereas increasing it ("High Fire" scenario) retards the process, causing the boreal zone to remain a C source until *ca.* 2025. These two scenarios lie somewhere between the Foothills Forest unmanaged scenario (Figure 4) and the "Harvesting-plus-Silviculture" managed scenario (Figure 5b). What other management options might be considered?

Figure 7 shows the results of projections assuming some technically feasible (but not necessarily economic) intensive management scenarios, first reported in Kurz et al. (1995b). All three management options produce long-term increases in C storage, but "Selective Conversion" (converting 5% of all areas carrying less than 2 Mg C ha^{-1} in biomass) takes up more C than the base run in all but the first 5 years. This is because C released from decomposable soil pools in the early stages of stand regeneration greatly exceeds any gains from increased biomass productivity. Hence limiting restocking and other regeneration operations to those areas with low initial biomass greatly enhances the regional C uptake. Under this scenario, the greatest increase in C uptake is achieved in the shortest time, advancing the switch from C source to C sink to the early 2000's. Compared to the "Base Run", the increase in average uptake for the period 1990–2040 under the "Selective Conversion" scenario would be about 47 Tg C yr^{-1}. Such an increase would represent a significant offset to the

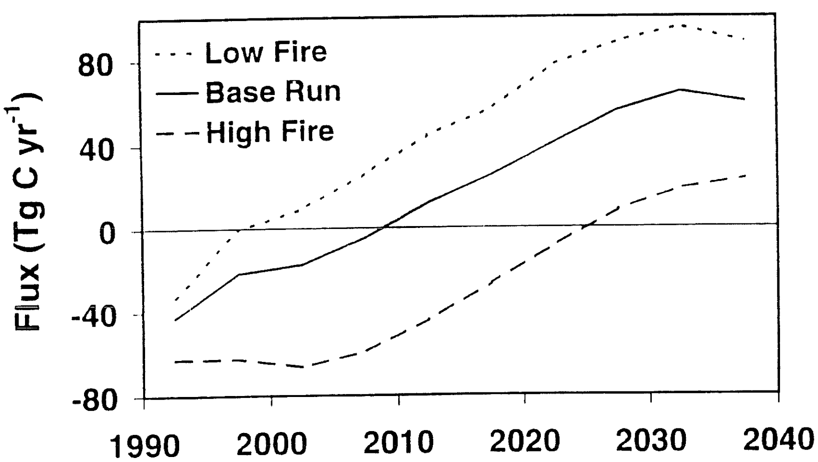

Fig. 6. Projected annual average net changes in total ecosystem C in Canadian boreal and subarctic forest ecosystems for the period 1990–2040 under three different assumed fire disturbance rates related to the rate observed in 1985–1989. Base Run: 60% Low Fires: 30%, High Fires: 120%. Positive flux indicates increased storage in the indicated component. (Redrawn from Kurz and Apps 1995.)

approximate 112 Tg C yr^{-1} currently emitted by Canadian fossil GHG sources (Marland et al. 1994). A program of this scale might be difficult to justify economically, and may not be realistic for ecological reasons—although it could bring benefits other than C sequestration. In any case, it provides an estimate of the upper bound to the possible GHG mitigation that could be achieved by managing Canada's boreal forest biome.

1.4.3 Carbon Storage in Wood Products

The foregoing points neglect any specific allowance for C storage in wood products, e.g., as shown in Figure 5. This aspect has been addressed in more detail, both in the forest-scale analysis (Price et al. 1996) and at the regional scale (Kurz et al. 1992; Kurz et al. 1995a). Only a few comments will be made here.

For the Foothills Forest FMA area, annual additions of biomass C to lumber products take about 130 years to balance losses, because of their relatively slow rate of decay (25-year half-life). Lumber products contribute much more to total C storage than pulp products, containing about 5.5 Tg C by *ca.* 2090. Although 50% more C is initially converted by the mills into pulp products, the balance between inputs and decay is reached after only 30 years with a pool size of about 1 Tg C. Some 90% of previously manufactured pulp products are ultimately discarded in landfills, however, and because some decomposition rates in

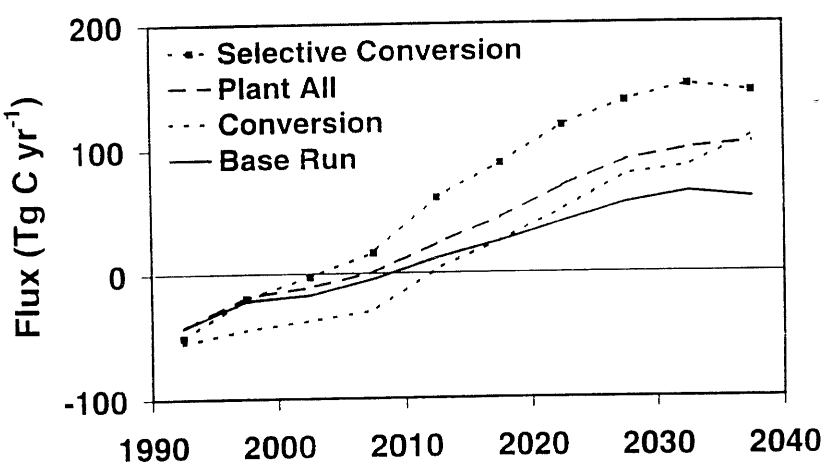

Fig. 7. Projected annual average net changes in total ecosystem C in Canadian boreal and subarctic forest ecosystems for the period 1990–2040 for the Base Run, and under three different assumed management scenarios: all disturbed areas planted, conversion of 1% of all non-stocked area per year, and conversion of 5% of all non-stocked areas carrying less than 2 Mg C ha^{-1} biomass. Positive flux indicates increased storage in the indicated component. (Redrawn from Kurz and Apps 1995.)

landfills appear to be very slow, considerable quantities of C are likely to accumulate there in the long term, contributing almost 50% of the total C storage in products after 250 years, and causing products to store perhaps 25% of that contained in forest biomass. The projected role of landfills as a future store of C is entirely dependent upon the assumptions made concerning product decay coefficients and the average environmental conditions likely to exist in the future; they do, however, point to an important area for research. Karjalainen et al. (1995) reached similar conclusions in a sensitivity analysis of C dynamics of the Finnish forestry sector.

In the Canadian boreal zone, 20.3 Mha (about 6.7% of total area) were harvested during 1920–1989 (Figure 2), transferring a total of 0.78 Pg biomass C to the products pool, of which 0.30 Pg C remained in wood products and landfills in 1989 (Kurz and Apps 1996, Figure 14.4), thereby contributing additional net C storage of about 4 Tg C yr^{-1} (distributed mainly within Canada and the USA). In 1989, C stored in wood products from Canadian boreal forests was about 4% of that in forest biomass (compared to 5% for Canada in entirety). Although long term projections are not available, the Foothills Forest would appear to be fairly representative of the boreal region (the current ratio of products C to biomass C is about 4%), so proportions of 10–15% might be achievable in the long term. Even greater storage might be achieved if better wood utilisation and preservation techniques are developed in the future.

It is worth noting that for Canada, the net increase in C stored in wood products (including those exported to other countries) was about 24 Tg C yr^{-1} for the period 1985–1989 (Kurz, 1996, unpublished data). More productive forests located elsewhere in Canada generate approximately 5 times the C storage in products from an area only one third of that occupied by boreal and subarctic forests. This is because (a) the boreal forests are still far from being fully exploited, and (b) the average ratio of long-lived to short-lived wood products is much smaller for the boreal than for more productive regions such as the coastal forests of British Columbia.

1.5 Discussion

Because the main thrust of this paper relates to boreal forests, and their potential for management to mitigate GHG emissions, no mention has been made of the role of the unforested peatlands which occur throughout the boreal and subarctic regions. Approximately 1 million km^2 of Canada's landscape, and well over 100,000 km^2 of Alaska and the conterminous U.S., are covered by peatland ecosystems. Calculating the C storage in these ecosystems is not easy, but Zoltai and Martikainen (1996) estimate that, globally, northern peatlands store about 397 Pg C (in living biomass and peat). In general, because peat accumulates in cool wet conditions, which prevent rapid decomposition, these peatlands represent a significant sink for atmospheric CO_2. Kurz et al. (1992), using a very simple model, estimated that Canada's peatlands take up approximately 26 Tg C yr^{-1}. There are two important points at issue. Firstly, peatlands, like forests, are vulnerable to disturbances, both natural and anthropogenic. It has been estimated that North American boreal peatlands release about 10 Tg C yr^{-1} due to fires (S C Zoltai, 1996, pers. comm., Canadian Forest Service). In addition, many northern peatlands are potentially sensitive to climatic change, with the likelihood that a warmer climate will produce faster decomposition and increased burning, causing some to become net sources of CO_2 and/or methane (e.g., see Oechel et al. 1993). Secondly, although management of peatland resources to conserve additional C is not practical, mismanagement may cause them to lose this important function. Where peatlands are to be exploited, this must be done carefully; elsewhere, conservation of peatlands should be an essential component of any global GHG mitigation strategy.

1.5.1 How Might Canada's Boreal Forests Mitigate Anthropogenic C Emissions?

Although relatively small areas of the Canadian boreal have been harvested in the past, this situation is likely to change as existing management plans are implemented and more remote areas are placed under management—a fact which must be considered in any assessment of the role of these forests in mitigating anthropogenic GHG emissions. Forest management activities can be classified into three categories: protection (from natural disturbances), productivity enhancement and harvesting. The effects of manufacture and utilisation of wood products are also potentially very important in any assessment of C storage and release from forest ecosystems. It should not be forgotten, however, that all such activities require some fossil energy consumption. Comprehensive assessment of all C flows involved in each activity is needed to assess where the greatest potential mitigation benefits can be achieved.

Protection: An increasing natural disturbance rate shifts forest age-class structure toward greater proportions of younger age classes, thereby decreasing the average age of the forest and the average C density in biomass. An increase in the proportion of area in younger age classes also increases the area in which decomposition rates are accelerated and detritus inputs reduced, leading to reduced C storage in soil and detrital pools (see also Harmon et al. 1990). Hence reducing the natural disturbance rate through protection reverses all these trends and leads to greater storage of C in the ecosystem than would occur naturally (Figure 5). But, as Kurz et al. (1995b) have noted, frequent natural disturbances are an integral component of boreal ecosystem function: successful protection against fire tends to increase susceptibility to insect attack as the average forest age increases. Hence, given the scale of Canada's forest estate, protection may delay disturbances, but it cannot be expected to prevent them indefinitely.

Given the evident strong correlation between warmer-than-average periods and increased rates of natural disturbances (certainly fire, and probably insect attacks (e.g., Volney 1996)), any systematic GHG-induced climate warming would almost certainly make forest protection programs more expensive, even to maintain disturbance rates at current levels. As conditions become more severe, the proportion of disturbance outbreaks which can be tackled successfully will decrease, while the area lost will increase, leading to greater C losses.

Productivity Enhancement: Techniques to increase the average quantity of C fixed in forest biomass in a given period include those which increase primary productivity (notably fertilisation and tree species selection) and those which reduce the delay in regeneration following disturbance. Forest fertilisation is prohibitively expensive except on high quality sites, and is unlikely to be practical on a wide scale. Moreover, fertiliser manufacture requires significant energy, often from fossil sources. Other silvicultural treatments such as thinning and density control cannot, in general, increase net C uptake by the forest, although they generally serve to increase the proportion of utilizable wood and/or its value. Increasing the production of high value wood products should lead to greater C storage, because such products will tend to have longer average lifespans.

Reducing the delay between disturbance and regeneration increases the average amount of C stored in forest ecosystems in two ways. Firstly, the average rotation length is reduced, so more biomass is produced in a given period. Secondly, decomposition of detritus and soil C pools may also be reduced because the period for which they are exposed to elevated surface temperatures is shortened (Kurz et al. 1995b). The planting scenarios considered in Table 1.1 produced significant increases in regional C storage for these reasons. Although they may require additional fossil energy to implement, artificial regeneration techniques therefore appear to be a potentially useful strategy to offset GHG emissions, as well as to mitigate feedback effects such as changes in species composition that may result from changes in climate.

Harvesting: In forest ecosystems where natural disturbances are an integral component, harvesting removes material which would otherwise burn or be consumed from the site, with the potential to place the C it contains in longer term storage than would occur in the forest (i.e., in wood products). It also reduces the expenses associated with protection, and may help to increase soil C accumulation in some cases (e.g., where it causes the incidence of intense fires to be reduced).

Where the harvest age exceeds the average natural disturbance interval, disturbance suppression leads to increased average forest age and hence a one-time increase in average forest biomass C density. As mentioned earlier, large-scale protection of mature boreal forest stands from insect attacks and fires is likely to be impractical, however, particularly if climate warming occurs. In such circumstances, harvesting may prove a useful strategy to reduce C losses from boreal forest ecosystems, and hence mitigate global GHG emissions. Better tree utilisation resulting from silviculture and improvements in harvesting techniques would also contribute to further reductions in C emissions, e.g., as discussed by Harmon et al. (1996).

Wood Products—Manufacture and Utilisation: Such a strategy would be enhanced if the average lifespan of wood products exceeds that of the woody material derived from dead trees decomposing in a similar unharvested forest. Hence, in the long-term, C stored in wood products would represent a reduction in net releases to the atmosphere. Regardless of the potential C storage in forest products and landfills, however, far greater C offset benefits are likely to be obtained from the use of wood products (including recycled materials) as fossil fuel substitutes, both directly and indirectly (Schlamadinger and Marland 1996, Nabuurs 1996, Matthews et al. 1996).

1.6 Conclusions

The results of these studies demonstrated that fluctuations in natural disturbance regimes of extensively managed and unmanaged forest ecosystems, (i.e., those not directly affected by land-use changes) can have significant impacts on net C fluxes between the biosphere and the atmosphere. The typical response for boreal forests in North America is triggered by a period of increased disturbances, which leads to increased losses due to decomposition of recently killed stands and causes a net C source. Following this, a period of reduced disturbances allows the increased area of younger forest stands to accumulate C, and once growth rates have increased to the point of C uptake exceeding the decomposition losses, the system reverts to a C sink. These transitions between net C sources and net C sinks may therefore take many years, although, because of the differing dynamics for growth and disturbances, sink formation will typically take longer than source formation. One important consequence of this effect is that *all* forest ecosystems must be considered in global C accounting, and not merely those created or destroyed by recent land-use changes.

Our conclusion that the boreal forests of Canada (and possibly of Alaska and Russia) were actually net sources of C after 1980 adds to the difficulty of reconciling ground-based observations with the results of deconvolution experiments such as those of Tans et al. (1990), and hence of closing the global C budget. The recent history of disturbances in Canadian forests may actually be contributing to variations in the rate of increase in the atmospheric CO_2 concentration as recently documented by Keeling et al. (1995). The period of reduced disturbance rates prior to 1980 would have contributed to a greater than average terrestrial C sink, while increased disturbances in the period 1980-1989 would have reduced it. The difficulties in balancing the global C budget may therefore be due in part to a failure to account for the effects of these disturbances to natural ecosystems which operate over decadal time scales. If the present observations for the Canadian boreal are more generally applicable, then any persistent increase in disturbance rate, as might result from climate warming, could turn existing sinks into sources, and possibly herald the beginning of a period of GHG-induced positive feedback.

Manipulations aimed solely at increasing biomass accumulation in forest ecosystems will tend to increase total C storage—but this must eventually reach a maximum and at the cost of increased investment in protection against natural disturbances. For those forests subject to frequent natural disturbance, harvesting may be a practical means of conserving C, since it both justifies the investment in protection and reduces protection costs, as well as potentially increasing the store of C in wood products. In rather exceptional cases, such as the managed forest discussed in this study, natural disturbance intervals may be shorter than the typical harvesting age. In such cases, protection from fires and other management practices can even increase ecosystem C storage relative to the natural forest.

Practical methods for overcoming the effects of possible climate change on forest structure are limited. Prompt regeneration of disturbed areas (natural or harvested) is one potentially useful strategy. This will also help to offset anthropogenic GHG emissions, together with silvicultural treatments which maximise the proportion of long-lived products. Using wood products to substitute for fossil energy (both directly and indirectly) is, however, likely to be a more effective means of using forest resources for GHG mitigation.

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