THE CARBON BUDGET OF THE CANADIAN FOREST SECTOR: PHASE I

W.A. Kurz,[1] M.J. Apps,[2] T.M. Webb,[1] and P.J. McNamee[1]

INFORMATION REPORT NOR-X-326

FORESTRY CANADA
NORTHWEST REGION
NORTHERN FORESTRY CENTRE
1992

[1] ESSA Environmental and Social Systems Analysts Ltd., 3rd Floor, 1765 West 8th Avenue, Vancouver, British Columbia V6J 5C6

[2] Forestry Canada, Northwest Region, Northern Forestry Centre, 5320 – 122 Street, Edmonton, Alberta T6H 3S5

Catalogue No. Fo46-12/326E
ISBN 0-662-19913-8
ISSN 0704-7673

This publication is available at no charge from:

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

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
Place du Portage
165, Hôtel-de-Ville
Hull, Quebec
J8X 3X2

Printed in Canada

CANADIAN CATALOGUING IN PUBLICATION DATA

Main entry under title:

The carbon budget of the Canadian forest sector. Phase I

(Information report ; NOR-X-326)
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-19913-8
DSS cat. no. Fo46-12/326E

1. Soils — Carbon content — Canada — Models. 2. Forest soils — Canada — Models.
3. Forest ecology — Canada — Models. 4. Forest biomass — Canada — Models.
I. Kurz, Werner Alexander, 1958- . II. Northern Forestry Centre (Canada).
III. Series: Information report (Northern Forestry Centre (Canada)) ; NOR-X-326.

S592.6.C35K87 1992 574.5'2642'0971 C92-099763-5

This report has been printed on Canadian recycled paper.

Kurz, W.A.; Apps, M.J.; Webb, T.M.; McNamee, P.J. 1992. *The carbon budget of the Canadian forest sector: Phase I*. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-326.

ABSTRACT

An assessment of the contribution of Canadian forest ecosystems and forestry activities to the global carbon budget was undertaken. The first phase of this study consisted of the development of a computer modeling framework and the use of published information to establish the sector's current role as a net source or a net sink of atmospheric carbon. The framework includes age-dependent carbon sequestration by living forest biomass, net detrital litter fall of carbon to the forest floor, subsequent accumulation and decomposition release in three soil compartments, retention of carbon in manufactured products derived from harvested forest biomass, and burning of forest biomass for energy. There is explicit representation of the role of ecosystem disturbances, such as fire, insect-induced stand mortality, and harvesting (clear-cutting, clear-cutting and slash burning, and partial cutting), as they affect carbon releases and transfers to the forest floor and to the forest product sector. Regrowth of biomass and changes in soil decomposition processes following disturbance are also simulated within the model. In the first phase of the work, national and provincial data bases were used to provide the first comprehensive estimates of the net carbon exchange between Canadian forest ecosystems and the atmosphere for the reference year 1986.

RÉSUMÉ

Une évaluation de la contribution des activités forestières et des écosystèmes forestiers du Canada au bilan mondial du carbone a été entreprise. La première phase de l'étude a comporté l'élaboration d'un cadre de modélisation informatique et l'utilisation de l'information publiée pour établir le rôle du secteur comme source nette ou puits net de carbone atmosphérique. Le cadre de modélisation tient compte de la séquestration du carbone par la biomasse forestière vivante selon l'âge, des apports nets de carbone au sol forestier par les chutes de litière, de l'accumulation subséquente du carbone et de sa libération par décomposition dans trois compartiments du sol, de sa rétention dans les produits tirés de la biomasse forestière et de la combustion de la biomasse forestière pour l'obtention d'énergie. Le rôle des perturbations affectant les écosystèmes, comme les incendies, la mortalité des arbres causée par les insectes et la récolte (coupe à blanc avec ou sans brûlage des rémanents et coupe partielle) est représenté de façon explicite, plus précisément pour ce qui concerne les effets sur la libération du carbone et le transfert de celui-ci dans le sol et les produits forestiers. La repousse de la biomasse et les changements touchant les processus de décomposition du sol après les perturbations sont également simulés. Dans la première phase du travail, des bases de données nationales et provinciales ont été utilisées pour produire les premières estimations globales du flux net de carbone entre les écosystèmes forestiers canadiens et l'atmosphère pour l'année de référence (1986).

FOREWORD

ENFOR (ENergy from the FORest) is a contract research and development (R & D) program managed by Forestry Canada. It is aimed at generating sufficient knowledge and technology to realize a marked increase in the contribution of forest biomass to Canada's energy supply. The program was initiated in 1978 as part of a federal interdepartmental initiative to develop renewable energy sources.

The ENFOR program deals with biomass supply matters such as inventory, growth, harvesting, processing, transportation, environmental impacts, and socioeconomic impacts and constraints. A technical committee oversees the program, developing priorities, assessing proposals, and making recommendations. Approved projects are generally carried out under contract.

General information on the operation of the ENFOR program, including the preparation and submission of R & D proposals, is available upon request from:

The ENFOR Secretariat
Forestry Canada
Place Vincent Massey
351 St. Joseph Blvd.
Hull, Quebec
K1A 1G5

This report is based in part on ENFOR Project P-387, which was carried out under contract by ESSA Environmental and Social Systems Analysts Ltd., Vancouver, British Columbia (DSS File No. 4Y080-9-0285/01-XSG).

This work was supported in part by the Federal Panel on Energy Research and Development (PERD).

CONTENTS

APPENDIXES

FIGURES

TABLES

NOTE

INTRODUCTION

Amounts of gases with heat-trapping characteristics, such as carbon dioxide (CO_2) and methane (CH_4), are increasing in the earth's atmosphere (Gammon et al. 1985; Keeling et al. 1982). Increases in CO_2 and other radiatively active gases are predicted to lead to a rise of 1.5–4.5°C in the average global surface temperature in the first half of the 21st century (Hansen et al. 1988; Schlesinger and Mitchell 1985). Currently, the net increase of carbon (C) in the atmosphere is in the order of 3×10^{15} g annually. The two primary anthropogenic sources of C are the burning of fossil fuels (ca. 5×10^{15} g C) (Rotty and Marland 1986) and deforestation associated with changes in land use (1.8×10^{15} g C) (Houghton 1986; Houghton et al. 1983).

Forests and forest sector activities play an integral role in the short-term (less than 100 years) dynamics of the global C cycle. Through photosynthesis, forests remove CO_2 from the earth's atmosphere and retain some of this C for decades or even centuries. Decomposition of dead organic matter, wildfires, and other disturbances release C back into the atmosphere. Forest harvesting transfers biomass C from forest ecosystems to the forest product sector, where it is converted into construction lumber, pulp and paper products, or energy. Each of these forms of end use has a different C-retention profile, resulting in different rates of C release into the atmosphere. The net flux of C between the forest sector and the atmosphere determines whether forests and forest sector activities are part of the problem or part of the solution with respect to changes in atmospheric CO_2 concentration.

Forests can contribute to increases in atmospheric CO_2 if, through deforestation and land-use change, large amounts of C are released into the atmosphere. There are, however, ways in which forests can contribute to strategies that limit the rate of atmospheric CO_2 increase. For example, large-scale afforestation increases the area of forest that actively sequesters C. Less obvious is the role of biofuel. The replacement of fossil fuel energy sources with fuels from biomass reduces the rate of fossil C input to the atmosphere; as long as the forest (or other vegetation) that provided the biofuel regrows, the use of biofuels for the production of energy is sustainable. Reductions in fossil C consumption decrease the rate at which inactive fossil C enters the active biospheric C cycle.

Canada occupies a large fraction of the global land mass and much of it is covered by forests. The net budget of C fluxes between the Canadian forest sector and the atmosphere may, therefore, be of significance to the global C cycle. An interest in quantifying the contribution of the Canadian forest sector to the global C budget resulted in this study, which consists of three phases. This report comprises the results of the first phase of the study: it addresses the status quo and provides a tool for conducting future analyses. The second and third phases of the study will address the impacts of climate change, the response of Canada's forest ecosystems, and the implications of various policy options for the forest sector C budget.

The specific objectives of the first phase were as follows:

1. to develop a conceptual framework of the C budget of the Canadian forest sector that includes the role of bioenergy production;
2. to calculate (based on the best available information) the annual net balance of the national forest sector C budget, and to provide an assessment of the uncertainties associated with this estimate;
3. to specify the assumptions in this budget; and
4. to identify major gaps and deficiencies in available data.

The importance of a comprehensive conceptual framework was recognized from the outset of this study. A well-tested approach (Holling 1979) was employed to bring together scientists and experts from a number of relevant disciplines in a workshop to review and modify a preliminary conceptual model and to identify data and information required for the model (see Appendix 1).

The conceptual framework, the analytical framework, and the C budget model are described in detail on pages 2–36. The results of several sensitivity analysis runs of the model are presented and discussed on pages 36–50, followed by a summary of future research needs. The appendixes of the report contain many background data compiled for the C budget model.

This report describes the Phase I model simulation of a single annual time-step for the reference year 1986. This reference year is defined by the choice of disturbance statistics, which represent an average year in the period 1980 to 1989. It must be emphasized, however, that the results reported should not be extrapolated beyond this single time-step because of the effects of known between-years variation and possible longer-term trends. The modeling framework is being expanded to better address temporal dynamics of the C budget.

General Overview

The objective of the conceptual framework is to account for all major C pools, transfer pathways, sources, and sinks, and to define the bounds of the system. The framework provides an overview of the conceptual understanding of the C dynamics of Canadian forests and forest sector activities.

The conceptual model of the C budget of the Canadian forest sector recognizes two major C pools: forest ecosystems and the forest product sector (Fig. 1). Forest ecosystems include two C pools: biomass and soils. The biomass C represents all living tree and plant biomass; the soil C pool includes C in detritus, forest floor, coarse woody debris, and soil organic matter. The forest product sector contains C derived from tree biomass harvested in Canada that may have undergone several conversion processes.

Carbon contained in biomass destined for the production of bioenergy is represented as a separate, short-term C pool (biofuel) because of the potential significance of its substitution for fossil C energy sources. By the same token, C released while generating energy from forest biomass (bioenergy) should also be accounted for within the forest product sector.

Forest ecosystems sequester C through photosynthesis. Carbon is released back into the atmosphere through microbial decomposition, respiration, and fires. In the absence of disturbances, the balance between net photosynthesis and decomposition determines the rate of net ecosystem C accumulation, which is calculated as the sum of net changes in the biomass and soil (including detritus) C pools.

Disturbances such as fire, harvesting, or pests affect the C content of stand components, both during the disturbance and for some time thereafter. Fire, for example, transfers C from biomass to soil C pools and rapidly releases some ecosystem C into the atmosphere as CO_2, carbon monoxide (CO), CH_4, nonmethane hydrocarbons (NMHC), and particulate matter. Harvesting removes a portion of the biomass C from the forest ecosystem and transfers it to the forest product sector. Harvesting also transfers some biomass C (slash and cull) to the detrital component of soil C pools. The impact of pests on the C budget of forest ecosystems depends upon the type of pest and the severity of the damage. Low or moderate pest damage may merely reduce the rate of C accumulation, whereas more severe or repeated pest damage can lead to a net ecosystem C release because of tree mortality and subsequent decomposition. Insect respiration also releases small amounts of C directly to the atmosphere.

Disturbances also influence stand development and may set the ecosystem back to an early successional stage. They affect both the future rate of C uptake by the regrowing or recovering vegetation, and the rate of C release from the decomposing C pools remaining after disturbances. The net change of ecosystem C following disturbance depends on many factors, including the type and intensity of disturbance, the amount of C in the main C pools prior to and after the disturbance, and the recovery rate of the ecosystem.

The conceptual model (Fig. 1) also identifies an aquatic pathway and an associated potential sink in sediments. Seepage from forest ecosystems may remove C in solution or as suspended particulate matter. Although the annual rate of C removal by this pathway may not be high, some of this C can be deposited in long-term sinks, such as lake or ocean sediments.

Inputs to the forest product sector originate from the harvesting of forest biomass and its removal from forest ecosystems. This biomass is converted into a large number of different forest products. Carbon releases to the atmosphere occur at different stages of the production process, and the finished products contain varying fractions of the C originally removed from the forest. The length of time that C is retained in a forest product depends on the product's characteristics and end use. For example, C contained in newsprint may be released into the atmosphere within a few months of production, but if the newsprint is transferred to landfills, some fraction of C may be retained for a very long time. Similarly, C contained in construction lumber may remain in this form for many decades.

Carbon from Fossil Sources

Fossil C sources are used in many processes throughout the Canadian forest sector and are treated in the conceptual model as secondary C sources that may become important in the evaluation of possible C management and strategies. Tree planting, silvicultural activities, fire suppression, pest management, and harvesting involve the use of energy sources that release C into the atmosphere. Similarly, the production of nitrogen fertilizers requires substantial energy inputs that should be taken into account if increased potential for C storage

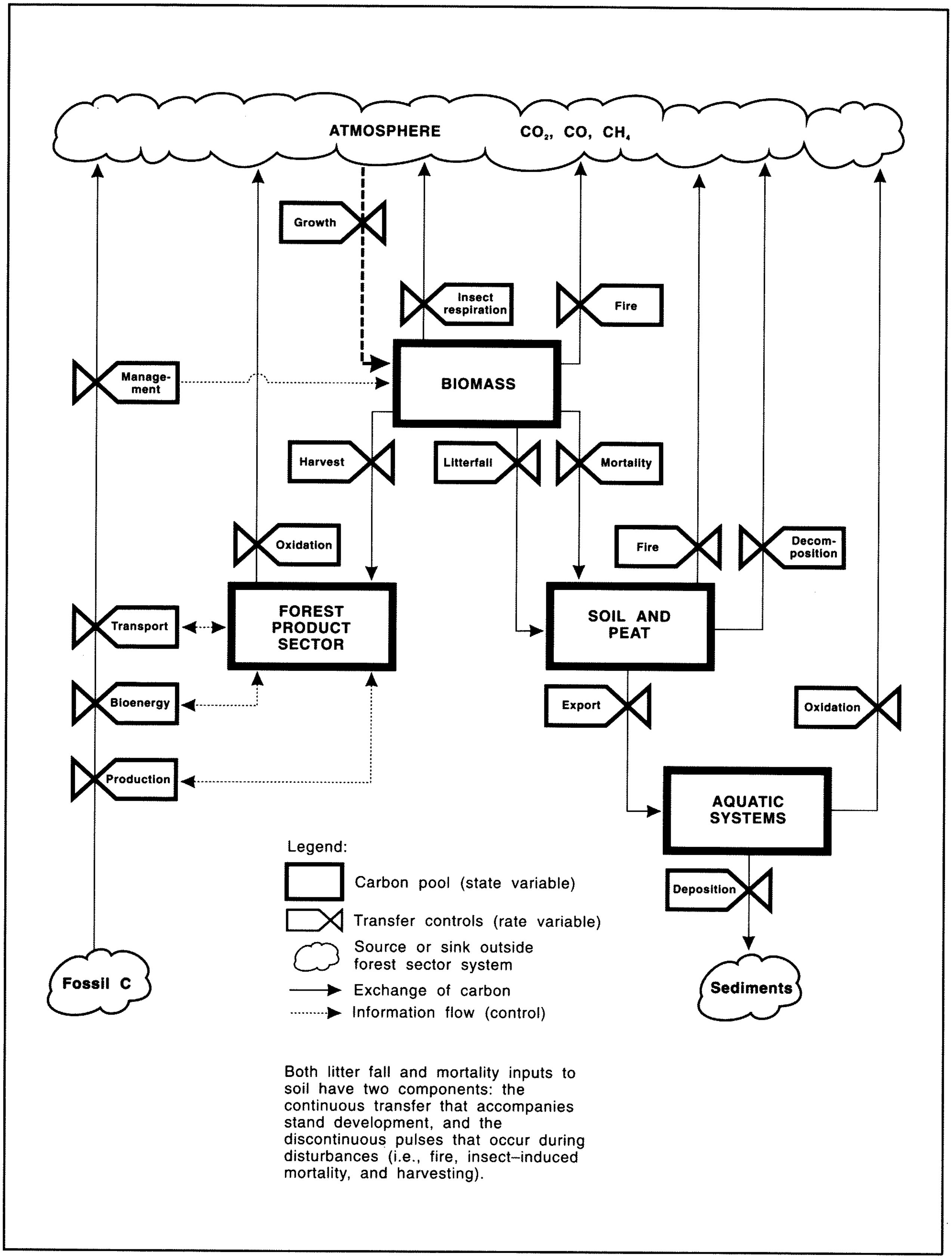


Figure 1. Diagram of the conceptual model of the carbon budget of the Canadian forest sector.

is a policy objective. Fossil energy is also used in transportation of the harvested wood and for many other processes of the forest product sector.

The conceptual model presented here includes these secondary C sources. The analytical framework contains the appropriate data records and analytical structure to address forest sector energy issues. Calibration data for secondary C sources and energy use in the forest sector, addressed in a separate study, will be incorporated in future developments of the C budget model.

Spatial and Temporal Bounding

The primary emphasis of the first phase of the C budget is on an evaluation of the existing Canadian forest land base under existing climate and management conditions. The analytical structure has been used to provide an estimate of the net C balance of the Canadian forests and forest sector activities for the reference year 1986. The primary data base making this task possible is Forestry Canada's Canadian Forest Resource Data System (CFRDS) (Bonnor 1985; Forestry Canada 1988; Gray and Nietmann 1989), which contains the biomass data (Bonnor 1985) needed for this study, based on almost complete coverage of forest land in Canada (see page 8 for a detailed description).

In the next phase, the analytical framework will be extended to permit simulations over a 100-year time-horizon. This length of time was chosen because it reflects the rotation age for many forest systems in Canada. Moreover, it is the time frame within which major policy decisions are required in response to predicted large-scale changes in climatic conditions resulting from the enhanced greenhouse effect.

Forest Sector

For the purpose of this C budget, the following assumptions regarding the scope of Canadian forests and forest sector activities have been made.

Land-use forms: All land areas included in the national forest biomass inventory (Bonnor 1985) are also included in the C budget model. In future analyses, changes in land use—such as the conversion of forests to urban land or the afforestation of marginal agricultural lands—will have to be considered in the C budget model. These land-use changes are not considered in the analysis of C dynamics for the single year 1986.

Peatlands: Forests in Canada may grow in areas classified as peatlands (peat depth greater than 50 cm), but only some peatlands are forested. The national forest biomass inventory contains no classifiers that identify peatlands, and the national peatland inventory (National Wetlands Working Group 1986) is not spatially referenced to the CFRDS database. Therefore, some spatial overlap (of unknown extent) exists in the areas covered by the two inventories. The current C budget model ignores the spatial overlap and separately accounts for peat accumulation, forest biomass, and soil C dynamics.

Carbon seepage into aquatic systems: Although recent reports (Kling et al. 1991) indicate that this pathway may be important, the lack of quantitative data prevents the inclusion of estimates of its contribution in the first phase of the model. The analytical structure is present in the Phase I model, but requires calibration data. It should be noted that the budget presented in Phase I may be affected if 1) there is a significant pool (e.g., sediment) associated with the aquatic pathway, and 2) this pool undergoes significant changes resulting from the disturbance of forest ecosystems.

Forest product sector: For the purpose of the C budget, it is necessary to follow wood products throughout their entire history: from the time when timber is cut and removed from the logging site until the time when the C it contains is released into the atmosphere or otherwise deposited in permanent storage.

Forest product trade: The Canadian forest product industry is heavily export-oriented. In 1987 Canada exported 41.7 million m^3 of lumber while importing 1.6 million m^3 (Forestry Canada 1989). To ensure a consistent C accounting system, all forest products generated from timber harvested in Canada are considered part of the Canadian forest sector, regardless of their ultimate end-use location. Forest products generated from biomass originating outside Canada are not considered part of the Canadian forest sector and are not included in the budget. All forest products that are part of the Canadian forest sector have been assigned C retention profiles, with no attempt made to account for possible differences between geographic regions of product end-use. This approach ensures that all C sequestered in Canadian forests is being tracked until it is released back into the atmosphere.

Design Criteria

The C budget model project has been initiated with a series of incremental, policy-relevant objectives. The objective of the first phase of the study was to provide a quantitative assessment of the current net C exchange between the Canadian forest sector and the global atmosphere. In subsequent phases, the potential impacts of global climatic change and forest management decisions on the C budget will be explored. The design of the analytical framework has taken into consideration model features required to meet the objectives of future phases of this study.

Research projects worldwide are investigating questions of global change, and it is anticipated that new scientific understanding will continue to emerge in the foreseeable future. This C budget model was therefore designed as a series of model components that make use of the best-available data and understanding. Should either the data improve, the scientific paradigms change, or alternative scientific hypotheses be proposed, it will only be necessary to modify model components to accommodate the new information.

In addition, all data used in the model are provided in external data files. This facilitates the sensitivity analyses that are used to explore the scientific uncertainties about data, model algorithms, and scenarios of future conditions.

The Phase I model was implemented on a desktop computer system to be able to take advantage of sophisticated user interfaces and programming language compilers. This decision imposed a number of data structure design constraints, particularly on computer memory management. The national forest biomass inventory, one of the primary sources of data, resides on a mainframe computer with large data storage capacity. The inventory, therefore, had to be aggregated before it was moved to the desktop environment.

Model Overview

The starting point of the C budget model is the national forest biomass inventory. This inventory is considered to have the best available data, with national coverage, on aboveground standing biomass pools and their dynamics. Disturbance data (such as fire, insects, and harvesting) are taken from provincial and federal data bases. The forest product sector is represented by a separate module that uses data on present and past forest harvesting activities.

The C budget model consists of five major computer programs (Fig. 2). The five programs must be run in sequence, because the first four prepare the data files and results that are used by the last program to generate output tables and summary reports. "Auxiliary data" files are identified in three locations in Figure 2. Each of these represents several additional data sources too complex to present in a single diagram.

Several other auxiliary programs have been developed to generate data files that are internally consistent with the requirements of the model. None of these programs modifies the basic input data other than by converting them into the file format required by the model.

File Conversion Module

The CFRDS at Petawawa National Forestry Institute (PNFI) supplied the basic biomass inventory data for each of the 12 provinces and territories. These data were extracted from Bonnor (1985) after aggregating spatial units and some of the classifiers represented in the inventory (see page 8). The first module of the C budget converts data files from the CFRDS into a binary file format and generates a header file containing a listing of all the categories of classifiers present in the individual data files. In this first module, data are merely aggregated and restructured into a format required for subsequent analyses.

Table-building Module

The dynamics of C in both the biomass and soil pools of forest ecosystems are represented in a series of look-up tables generated by the second module before execution of the main C integration module. This second module incorporates most of the scientific assumptions about ecosystem C dynamics in both the biomass and soil C pools. Forest ecosystems in each spatial entity in the model are stratified by several classifiers (e.g., forest type and productivity class). The look-up tables correspond to the possible combinations of these classifiers, and contain data describing soil and biomass C dynamics for the full range of stand ages typically encountered. Data on C dynamics are generated only for those combinations of classifiers that also contain data in the biomass inventory. All others are assumed to contain no C and therefore have no influence on the C budget.

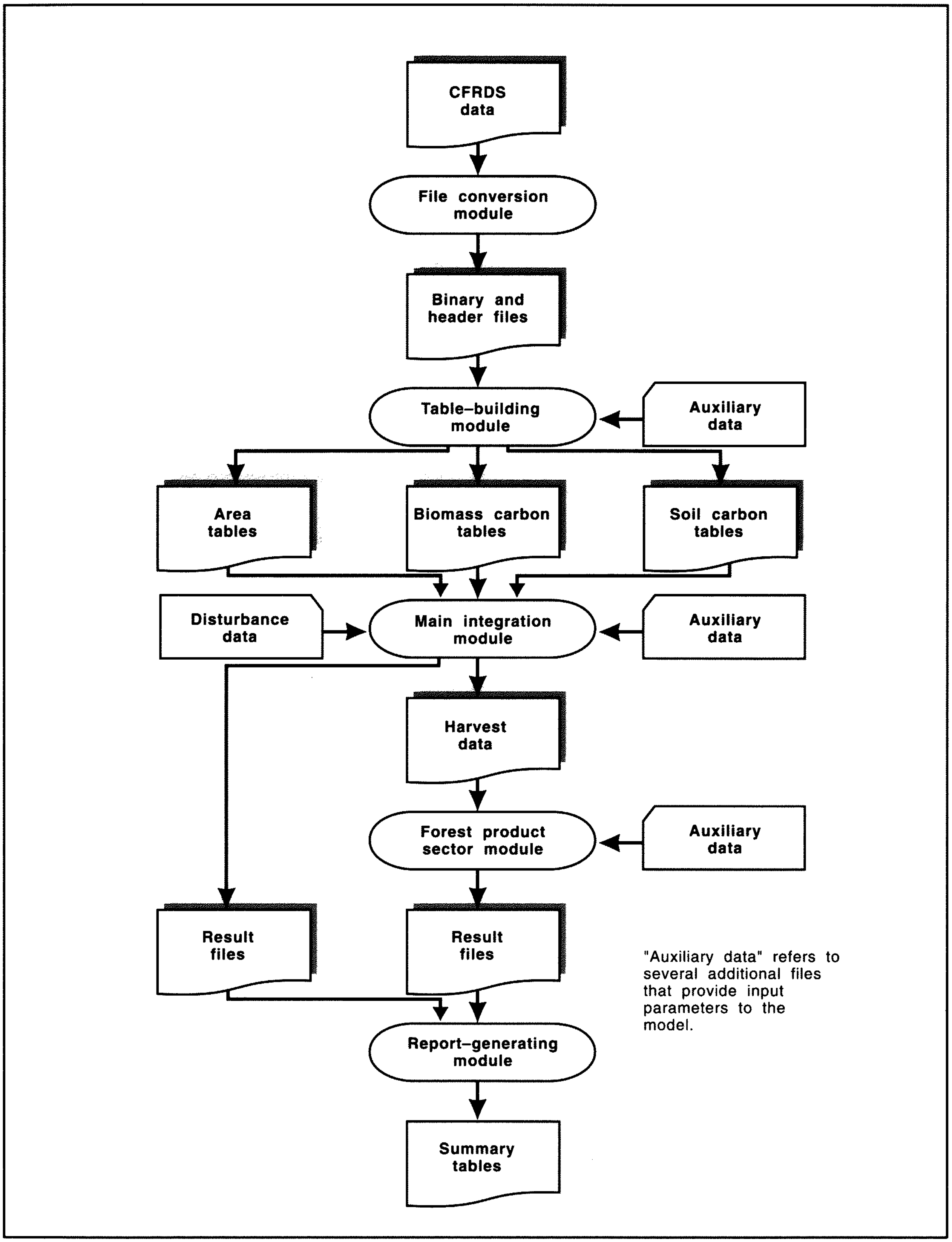


Figure 2. Simplified flow diagram of the carbon budget model, presenting the five main program modules and the major data files.

Five look-up tables are generated by this module. The first table contains the area represented by each combination of classifiers and the distribution of the area in 5-year age classes. Biomass and soil C dynamics are represented by two tables each: one table contains the C pool size, and the second table describes the annual rate of change of the pool size. Details of how the tables are generated and of table structure are described on pages 8–36.

The conversion of units for biomass and soil data to tonnes of C per hectare is also performed in this module. These C units are used by all subsequent modules.

Main Integration Module

The third module integrates all available information on biomass and soil C dynamics and on the impacts of annual disturbances. The disturbance types currently represented in the model are wildfires, insect-induced stand mortality, clear-cut logging, clear-cut logging with slash burning, and partial cutting. This module applies the annual disturbances of the five basic disturbance types to the areas affected, thus accounting for the C fluxes associated with the disturbances. Data requirements and the treatment of disturbances are explained in detail on page 18.

The main integration module generates two types of output files: one quantifies the transfer of harvested C from forest ecosystems to the forest product sector; the second provides the budget statistics for each spatial unit and for a large number of variables such as the net C change for each biomass and soil C pool.

Forest Product Sector Module

The forest product sector module receives input from the third module. It also uses several additional data files containing historic harvest data and other parameters required to quantify C fluxes in the forest product sector. The forest product sector module generates and maintains an inventory of forest products that originate from historical harvesting activities. Each of these product types has a characteristic C retention curve, which is used to simulate the release of C from the pool of forest products. The amount of energy required for the production of forest products, and the source of that energy (e.g., fossil fuel, bioenergy, hydroelectricity, and nuclear fission), can be accounted for within the forest product sector module. Data collection for the calibration of parameters on energy use and requirements is planned for the next phase of this study.

The forest product sector module also directs a user-specified proportion of the harvested material toward bioenergy production. The release of C from the burning of biofuels is accounted for, but there is no accounting in the Phase I model for bioenergy substitution of fossil energy sources. This accounting is planned for the next phase of this study.

Report-generating Module

The final module of the C budget model uses the output files from the main integration module and the forest product sector module, and generates summary output tables. This module allows modifications to be made to the format of the tables, the variables to be reported, and the stratification of the output.

Temporal and Spatial Dynamics of the Model

The C budget of the first phase of this study has been developed to assess the current annual net exchange of C between the Canadian forest sector and the atmosphere. Although the overall structure of the model has been designed and implemented for a dynamic simulation model, only one year (1986) is explicitly simulated in the first phase of the study reported here. During this single year, however, C is taken up or released into the atmosphere by forest ecosystems in different stand development stages, and C is released into the atmosphere from the forest product pool that contains C harvested during the years 1947–1986.

The model recognizes 41 explicit spatial entities that arise from overlaying provincial and territorial boundaries with the boundaries of the ecoclimatic provinces (see page 9). The spatial entities are geographically abstract in that actual geographic location and spatial arrangement have no implications for the Phase I C-budget model. Some parameter values (e.g., mean annual temperature), however, depend on the ecoclimatic province that is simulated and are attributes of each spatial unit. Because of the spatial independence of the C budget model, it could be applied readily to any other spatial entity, such as a forest region, a watershed, or a different nation. The ability to simulate the C dynamics at variable spatial scales could be used to validate the model—for example, by comparing the model results with the data available for a specific forest ecosystem.

Biomass Inventory Data

The inventory of forest biomass in Canada, a national data base, has been compiled from provincial and territorial inventories (Bonnor 1985). It contains spatial references to nearly 50 000 mapping cells of variable size. A set of classifiers (including land class, forest type, maturity class, etc.) and a set of attributes (including area of forest land, forest biomass, etc.) are attached to every cell. An average cell contains 15 records that refer to forest stands with unique combinations of classifiers.

The spatial resolution of the national inventory is unnecessarily detailed for a C budget model of national scope. It was therefore decided to aggregate the national inventory using ecoclimatic regions (Ecoregions Working Group 1989). This classification recognizes broad vegetation types and has already been used in Canadian studies of potential vegetation responses to $2 \times CO_2$ climate change scenarios[1] (Rizzo and Wiken 1989; Zoltai 1988). Figure 3 shows the map of the ecoclimatic regions of Canada (Ecoregions Working Group 1989) and identifies the 10 ecoclimatic provinces. The ecoclimatic regions of Canada are characterized by distinctive ecological responses to climate as experienced by vegetation and reflected in soils, wildlife, and water (Ecoregions Working Group 1989).

For the purpose of this study, the boreal ecoclimatic province was divided along the Ontario–Manitoba border into an eastern and western component, approximating the distinction between subhumid (west) and moist (east) boreal ecoclimatic regions. Forestry Canada staff at PNFI digitized the maps of ecoclimatic regions, created a new overlay with the national forest biomass inventory, and assigned the corresponding ecoclimatic province code to each of the spatial cells. The resulting data base was summarized, using ecoclimatic provinces within administrative provinces and territories as the smallest explicit spatial units. The new database recognizes 41 spatial units, each with a unique combination of administrative province and ecoclimatic province codes.

The national biomass inventory uses a stratification system with 13 classifiers (Bonnor 1985). When the inventory was aggregated from 50 000 cells to 41 spatial units, the number of classifiers was reduced from 13 to 6, eliminating unnecessary information such as access code and ownership. Table 1 lists the six remaining classifiers, as well as two additional classifiers (administrative province and ecoclimatic province), that characterize the records in the C budget data base.

For each spatial unit, only a subset of the possible combinations of these classifiers was actually present. For example, high site-productivity classes encountered in the Pacific Cordilleran ecoclimatic province do not occur in the Subarctic. Each record (i.e., combination of classifiers) in the national inventory data base contains several attributes describing the area represented and the biomass per hectare. Area information is always available, while biomass data exist for most records. Biomass is reported as area-weighted, oven-dry, mean biomass in tonnes per hectare for several biomass components.

Eight aboveground biomass components and their sum are recognized in the C budget model (Table 2). Although coarse-root biomass can be derived from allometric relationships, data with national coverage are not readily available, and coarse-root biomass is not addressed in the Phase I model. Even fewer data are available on ephemeral fine roots, and therefore no attempt was made to estimate belowground living-root biomass. As outlined in the description of the soils module, the contribution of fine-root detritus to soil C dynamics is recognized and included in that module. Estimation of root biomass and its dynamics will be undertaken in the next phase of this study.

The biomass data base of the C budget model recognizes the three forest types defined in the national biomass inventory, as well as an "unclassified" category. In the softwood forest type, 76–100% of the canopy consists of coniferous tree species; in the mixedwood forest type, 26–75% of the canopy is coniferous; and in the hardwood forest type, 0–25% of the canopy is coniferous.

In British Columbia, seven site-quality classes are recognized, compared to four classes in all other provinces. In the inventory, site quality classes 6 and 7 contain small areas and were therefore combined into a single class (6+) to reduce the complexity of the data base.

[1] The $2 \times CO_2$ scenario refers to the projected climate change that is expected to result from an effective doubling of the greenhouse gas concentrations in the atmosphere relative to the preindustrial CO_2 levels (280 ppm). The current level is approximately 350 ppm.

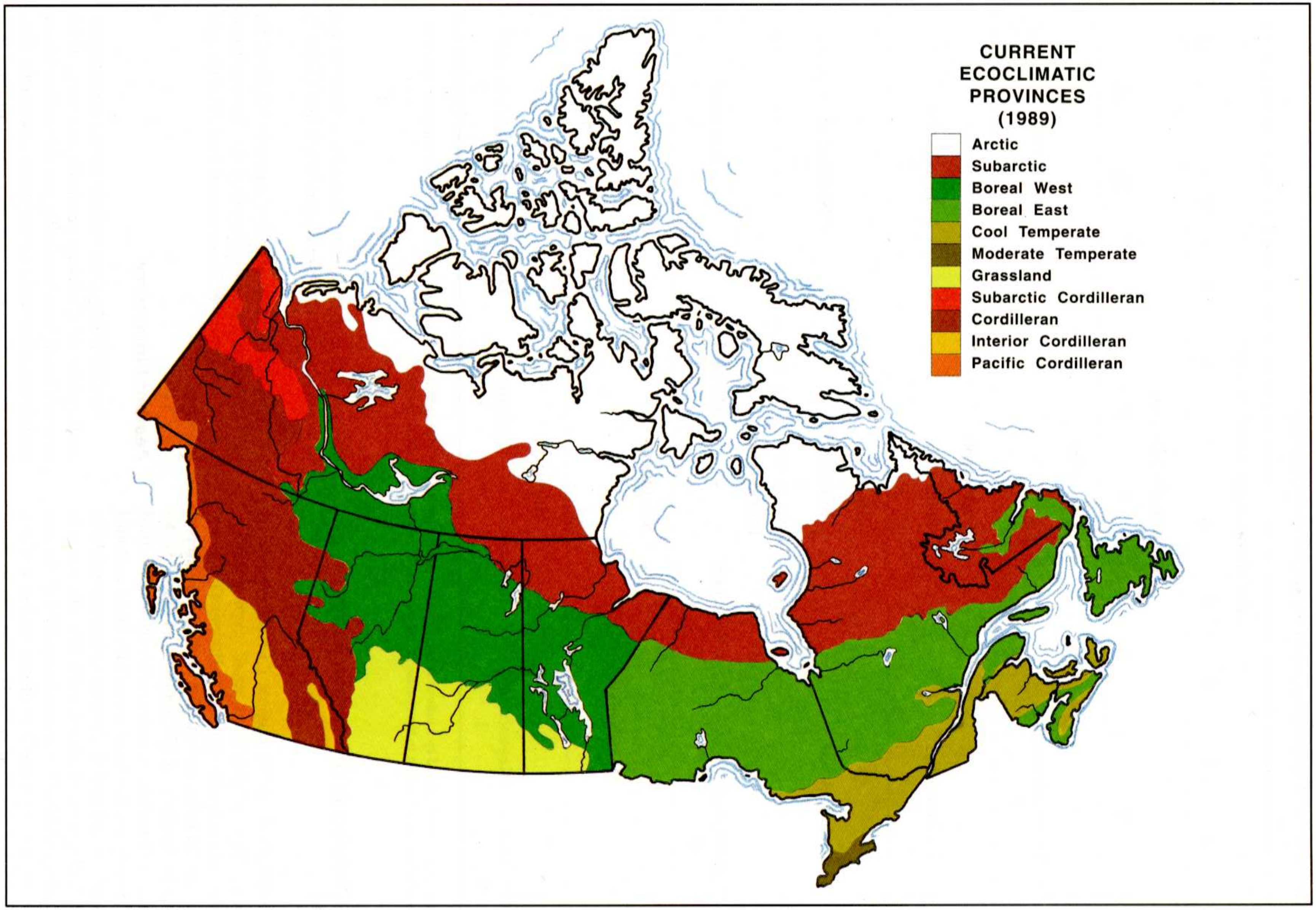


Figure 3. Ecoclimatic regions of Canada (source: Ecoregions Working Group 1989).

Table 1. System of classifiers used in the carbon budget model[a]

Administrative province/territory

1	2	3	4	5	6	7	8	9	10	11	12

Ecoclimatic province

1	2	3	4	5	6	7	8	9	10	11

Land class

Undetermined	Forest	Nonforest
9	1	2

Productivity

Undetermined	Productive	Nonproductive
9	1	2

Stocking

Undetermined	Stocked	Nonstocked
9	1	2

Forest types

Undetermined	Softwood	Mixedwood	Hardwood
9	1	2	3

Site quality

Undetermined						
9	1	2	3	4	5	6+

Maturity

Undetermined	Regeneration	Immature	Mature	Overmature	Uneven-aged
9	1	2	3	4	5

[a] Each spatial unit is referenced by a unique combination of administrative province and ecoclimatic province codes. Within each spatial unit, forests are further stratified according to the remaining six classifiers. Adapted from Bonnor (1985).

Area Statistics in the Carbon Budget Model

Modifications to the original CFRDS reported in Bonnor (1985) have resulted in small inventory differences between statistics reported in Bonnor (1985) and those presented in this report. The total land area represented in the inventory is 578.3 million ha (Table 3). An additional 64.8 million ha in the inventory are classified as water surfaces, but these areas have been excluded from the C budget model. Biomass values are available for 404.2 million ha, which represent 70% of the area in the inventory (Table 3). The remaining 30% of the area in the inventory is primarily nonforest land or unclassified land. Land classified as forest represents 76.3% of the total area in the inventory, and 42% of the total area in the inventory is classified as productive land (Table 3).

Four ecoclimatic provinces represent 82.3% of the total land area in the inventory (Fig. 4). The two boreal ecoclimatic provinces alone account for 43% of the total land area.

Peatland Inventory

The CFRDS data base contains no reference to peatlands, while the Canadian peatlands inventory, which accounts for all lands containing peat thicker than 50 cm, contains no reference to forest type or ecoclimatic province. Peatland areas are not necessarily distinct from

Table 2. Eight aboveground biomass components recognized in the biomass data base

Softwood	
Merchantable stem	The stem wood and stem bark of stems of merchantable size, defined by a minimum diameter at breast height, excluding the stump and tree top.
Merchantable foliage	The foliage biomass of the stems of merchantable size.
Other merchantable biomass	Other aboveground biomass from trees of merchantable size: branches, top, and stump wood.
Submerchantable trees	All other aboveground stand biomass.
Hardwood	
Merchantable stem	The stem wood and stem bark of stems of merchantable size, defined by a minimum diameter at breast height, excluding the stump and tree top.
Merchantable foliage	The foliage biomass of the stems of merchantable size.
Other merchantable biomass	Other aboveground biomass from trees of merchantable size: branches, top, and stump wood.
Submerchantable trees	All other aboveground stand biomass.
Total	Sum of all eight biomass components listed above.

Note: Merchantability definitions vary between provinces and define a minimum top diameter inside bark. See Appendix 1A in Bonnor (1985) for exact definitions of terms and diameter limits.

some of the forest area already in the inventory, but the extent of overlap cannot be determined from current data. Peatland C dynamics, which are calculated independently of biomass and soil C dynamics, are described in a separate data file containing three tables: the total area of peatlands stratified by ecoclimatic province and province, the net uptake of C, and the release of methane for the same peatland areas. In these tables, an average net C accumulation rate of 28 g C m^{-2} yr^{-1} is assumed (Gorham 1988; S. Zoltai, personal communication, April 1990). Appendix 2 contains the three tables summarizing the peatland data used in this study.

In the first phase of the study, the information from these tables has been added to the summary tables of the C budget, based on the simple view that peat formation and soil C accumulation from tree biomass are independent processes, even though they may occur within the same land area. Accordingly, it has been assumed that, in those areas where the two inventories overlap, the net C uptake in peat is additive to that of the biomass and soil C pools.

In the next phase of this study, peatland areas within the biomass inventory will be identified. The net C exchange will be computed using rates specific to ecoclimatic provinces (rather than an average rate for all of Canada) because predicted changes in climate are expected to influence future peat C accumulation differently in different regions.

Biomass Carbon Dynamics

The dynamics of forest biomass accumulation in forest stands are a central component of the C budget. The rates at which C is sequestered in forest biomass and soil C pools determine the forests' abilities to remove C from the atmosphere. On a national scale, surprisingly little is known quantitatively about the rates at which different forest ecosystem types sequester C. Although detailed ecosystem or stand growth models are available for a few specific ecosystem types, there are at present no models that provide information for all forest types in Canada.

For this study, net biomass accumulation curves were constructed from each unique combination of classifiers (i.e., administrative province, ecoclimatic province, land class, stocking, productivity class, forest

Table 3. Area represented in the carbon budget model and its stratification by productivity and land class ('000 ha)

Area type	Ecoclimatic province											Total area
	Arctic	Subarctic	Boreal West	Boreal East	Cool Temperate	Moderate Temperate	Grassland	Subarctic Cordilleran	Cordilleran	Interior Cordilleran	Pacific Cordilleran	
In inventory	3 499	136 439	114 663	134 483	35 584	2 082	6 127	14 733	90 676	19 381	20 605	578 273
With biomass	648	85 238	97 597	120 234	25 688	200	2 592	898	47 373	14 627	9 147	404 241
By productivity class												
Productive	0	16 629	55 896	79 199	24 388	279	2 597	136	41 294	14 394	7 699	242 512
Unproductive	648	70 458	44 284	47 812	2 231	15	81	4 132	19 950	915	2 906	193 433
Undetermined	2 851	49 352	14 482	7 472	8 965	1 788	3 449	10 465	29 431	4 073	10 000	142 329
Total	3 499	136 440	114 663	134 483	35 584	2 082	6 127	14 733	90 675	19 382	20 605	578 274
By land class												
Forest	648	88 971	103 021	127 011	26 619	294	2 701	4 268	61 340	15 309	10 606	440 790
Nonforest	2 550	43 237	10 546	7 436	8 963	1 788	3 426	6 692	29 324	4 073	10 000	128 033
Undetermined	301	4 232	1 096	35	2	0	0	3 773	12	0	0	9 451
Total	3 500	136 439	114 663	134 483	35 584	2 082	6 127	14 733	90 675	19 382	20 605	578 274
In peatland inventory[a]												
Total	741	18 005	42 480	27 529	1 407	23	0	75	1 825	0	1 429	93 513

[a] Included for reference.

Note: Totals may not add up due to rounding.

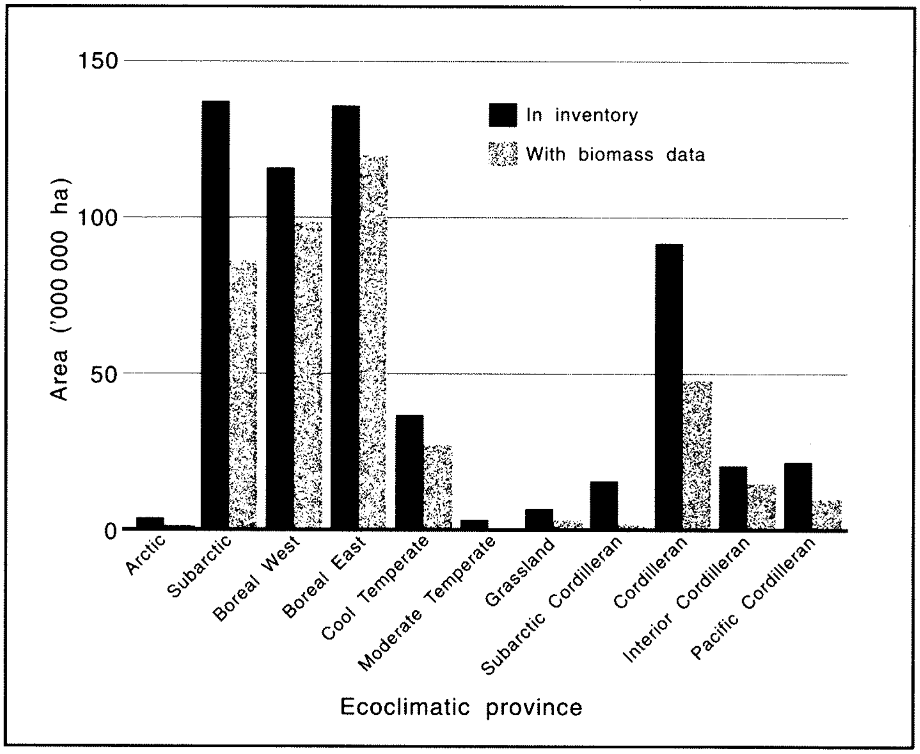


Figure 4. National biomass inventory data on land area by ecoclimatic province, as used in the carbon budget model.

type, and site quality) by treating the data in the associated maturity classes (i.e., regenerating, immature, mature, and overmature) as chronosequence data. This calculation is described in greater detail on page 14.

This approach maximizes the use of the inventory data and appears to be appropriate for most combinations of the classifiers. It can, however, yield indeterminate (or even biased) results when certain classifiers are not fully specified in the data bases. For example, there are situations where site quality is "undetermined" for all stands in a maturity-class sequence. Net biomass accumulation curves constructed from such data may be biased if site-quality classes are not uniformly represented in the different maturity classes. More typically, however, the "unclassified" site-quality class would be expected to contain average data for all site classes across all maturity classes, with the derived biomass accumulation curve adequately representing these average conditions.

The national forest inventories contain the most recent available data of the inventoried land area. The time since last inventory varies between and within provinces. In some parts of the country, the inventory data were collected in the 5-year period preceding the inventory date. In other parts, the information was collected as much as 20 years earlier. Each stand in the inventory has the year of the inventory attached to it, but this information was not retained in the aggregated data base. When using the national inventory it is common practice not to update stand age and other stand attributes relative to the date at which the inventory information was collected. No attempt has been made to update the maturity class assignments of older data sets contained in the inventory because too many assumptions about stand dynamics and disturbance impacts would be required.

Age Definition for Maturity Classes

Stands in the inventory are assigned to one of six maturity classes: regeneration, immature, mature, overmature, uneven-aged, or unclassified. The definition of the age classes that correspond with the maturity classes depends on the provincial and territorial inventories from which the data were originally derived. The age-class definitions are not part of the summary publication (Bonnor 1985) and are not contained in the biomass inventory.

Maturity classes represent a range of stand ages and are therefore not adequate, by themselves, for the construction of biomass-over-age curves. Additional information was available from *Canada's Forest Inventory 1986* (Forestry Canada 1988; Gray and Nietmann 1989). This inventory is an upgrade of *Canada's Forest Inventory 1981* (Bonnor 1982), from which the 1984 biomass inventory was derived. The 1986 inventory covers the same area (with minor differences) as the 1984 inventory, and in many cases it uses the same provincial inventory information. It also contains both maturity classes and 20-year age classes. When information for both maturity classes and age classes was available from the 1986 forest inventory, the two classifiers were used to compile tables that relate maturity classes to age classes for each province and forest type in Canada (Fig. 5; Table 4). The tables also contain the area-weighted average age for each maturity class.

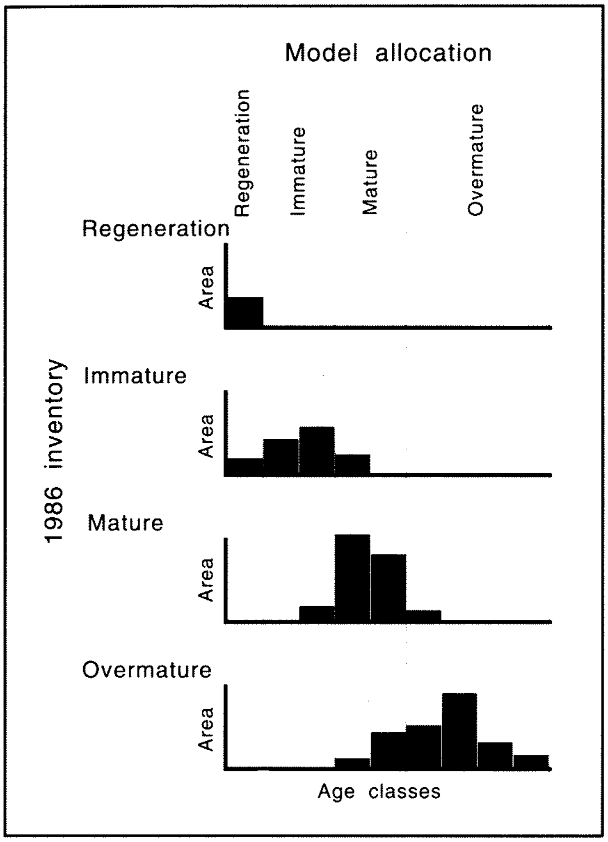


Figure 5. Example of the area distribution, by 20-year age classes, in each of the four maturity classes in the 1986 forest inventory, as allocated in the model.

The age-class versus maturity-class tables were used to define the age range for each maturity class. Age-range definitions of the maturity classes are required for two purposes: they are used to assign ages to the areas represented by each maturity class, and, together with the biomass data, they form the basis for the biomass accumulation curves. In many cases (as shown in the example in Table 4) the maturity-class versus age-class relationships were not clearly delineated and maturity classes overlapped somewhat, because not all factors that influence the maturity-class versus age-class relationship are accounted for in the classifiers used in the C budget model. For example, the relationship depends on tree species, but in the biomass inventory (and therefore the C budget) only forest types (softwood, mixedwood, and hardwood) are recognized, not the predominant species.

The upper and lower age boundaries of each maturity class were selected to ensure that there was neither an overlap nor a gap between adjacent maturity classes. When the tables showed an overlap in the maturity classes, the age boundary was redrawn so that the area excluded from one maturity class would approximate the area included in the adjacent maturity class (Fig. 5). Appendix 3 contains maturity-class definitions used in the model for all provinces and territories.

It was impossible to obtain reliable age-range definitions for the maturity classes used in the Yukon. The inventory forester responsible expressed some concern about the accuracy of the maturity-class assignments in the Yukon data of the national inventory because, for much of the area, these assignments were based solely on remotely-sensed data (C. Boyd, personal communication, May 1990). For this reason the maturity class "undetermined" was assigned to all records in the Yukon portion of the data base. The maximum age for forest stands in the Yukon was set at 150 years, although it is recognized that older stands do exist.

The process of converting the average biomass value of a maturity class into a sequence of biomass-over-age data pairs may introduce a discrepancy between the total biomass estimates that result from the C budget model and the estimates obtained from Bonnor (1985). The CFRDS data base, which was the basis for Bonnor (1985), has since been slightly revised. It is therefore not possible to attribute the small difference between the C budget results and those of Bonnor (1985) either to methodological bias or to the data base changes.

Conversion of Biomass to Carbon Values

The entire C budget model operates on units of C; all pool sizes and C fluxes are expressed in units of C, and all data on oven-dry biomass are converted to units of C by multiplying by a factor of 0.5 (the average C content of woody biomass). (See Bonnor [1985] for methods used to convert wood volume to biomass estimates.) Gaseous measurements of CO_2 can be expressed in C equivalents by dividing the CO_2 value by 3.667 (stoichiometric ratio).

Biomass Carbon Accumulation Curves

Biomass accumulation curves were constructed from the inventory data for each unique combination of classifiers (e.g., province, ecoclimatic province, land class, productivity, stocking, forest type, and site quality). Biomass data exist for 380 unique combinations. For each such combination, four or fewer data points are used to describe quantitatively the biomass at different stages in stand development (regeneration, immature, mature, and overmature). Biomass-over-age curves were constructed, using linear interpolation between the data and the following rules:

Table 4. Example of the relationships between age-class and maturity-class definitions

Data from 1986 inventory					Model allocation	
Age class (years)	Maturity class				Assigned maturity class	Age range (years)
	Regeneration	Immature	Mature	Overmature		
	Area (ha)					
1–20	656	84	0	0	Regeneration	1–20
21–40	0	8 213	0	0	Immature	21–60
41–60	0	11 757	26 654	0		
61–80	0	1 065	29 217	1 894	Mature	61–100
81–100	0	0	5 124	2 482		
101–120	0	0	2 566	1 707	Overmature	100–180
121–140	0	0	3	2 184		
141–160	0	0	3	224		
161+	0	0	0	178		
Unclassified	0	556	825	311	Unclassified	1–180
	Total area (ha)					
	656	21 675	64 392	8 980		
	Average age (years)					
	10.00	42.16	64.85	102.84		

Note: These tables were generated from the data contained in Canada's Forest Inventory 1986 (Forestry Canada 1988) for stocked, productive forest land. Assignments of maturity classes in the right-hand column are made to minimize the amount of overlap in the age-class ranges. The average age represents the area-weighted average.

1. The area-weighted average age was assigned to each maturity class along with the associated biomass.

2. The slope of the line between the two lowest age data was used to extrapolate to age zero (Fig. 6; pane 1). Two exceptions were made: if the extrapolation led to negative biomass, the age-zero biomass was reset to zero (Fig. 6; pane 2); and if the biomass in the regenerating phase was higher than in the immature phase, the age-zero biomass was set equal to that for regeneration (Fig. 6; pane 3).

3. For stands older than the oldest available data, a constant biomass was assumed (Fig. 6; pane 4).

4. The same rules were applied if fewer than four data points were available (Fig. 6; pane 5).

5. If only one data point existed (e.g., where no maturity classes had been assigned), forest biomass was assumed to have increased linearly from zero to the value defined in the biomass inventory and to remain constant thereafter (Fig. 6; pane 6).

Area Distribution within Maturity Classes

Forests of different ages have differing C accumulation characteristics (Fig. 7). To compile a national C budget, it was therefore necessary to ascertain the age-class distribution of these different forests. In addition, the area associated with each age class had to be determined. To obtain the age-class distribution, Bonnor (1985) was used to obtain the total area in each maturity class for each of these unique forest stands (i.e., unique combination of classifiers). Then the upper and lower ages associated with each maturity class were determined (as described on page 13). Finally, the area assigned to each maturity class was assumed to be uniformly distributed across all ages within that maturity class (Fig. 7).

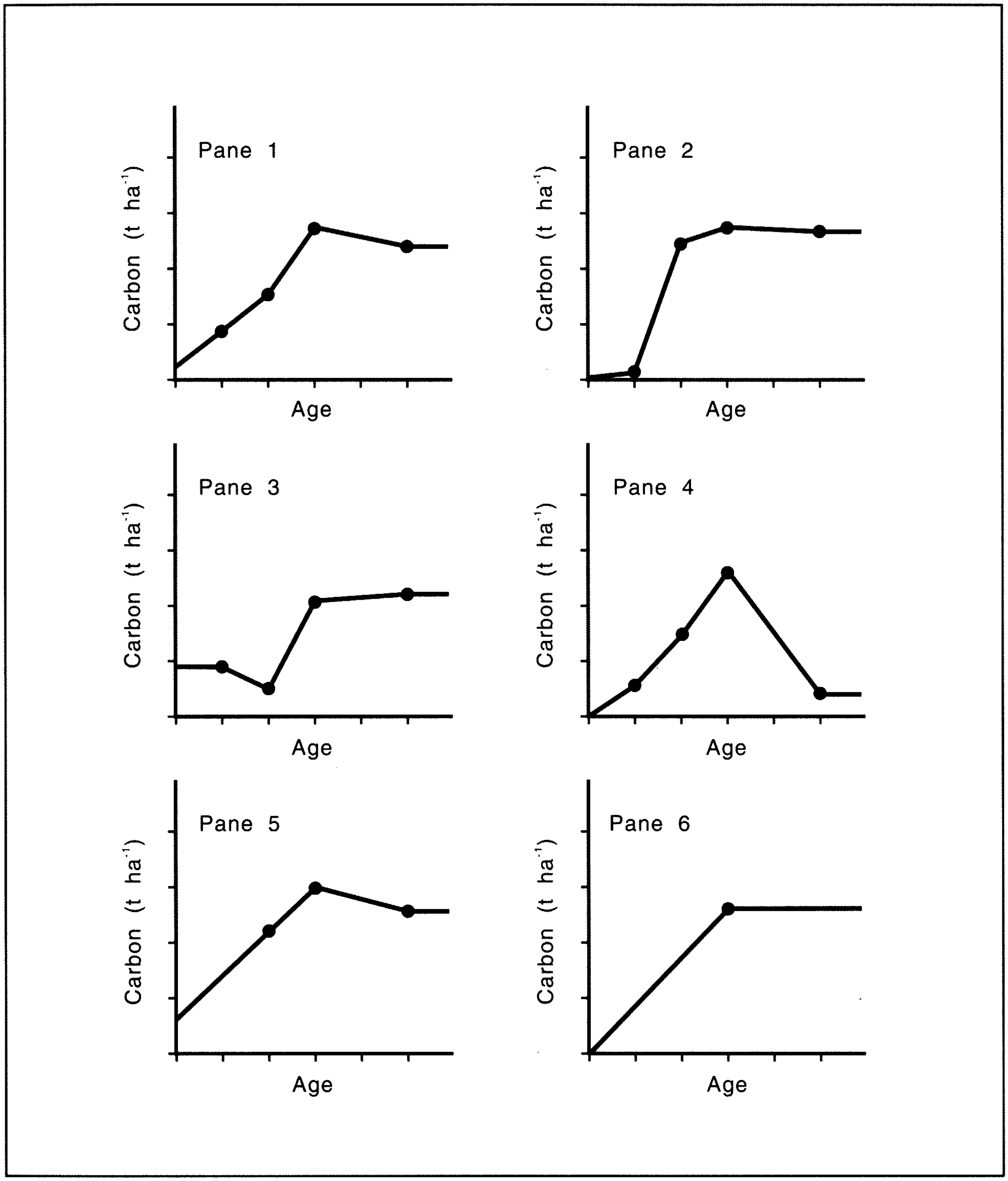


Figure 6. Net carbon accumulation curves that demonstrate the basic rules for deriving curves from biomass data points.

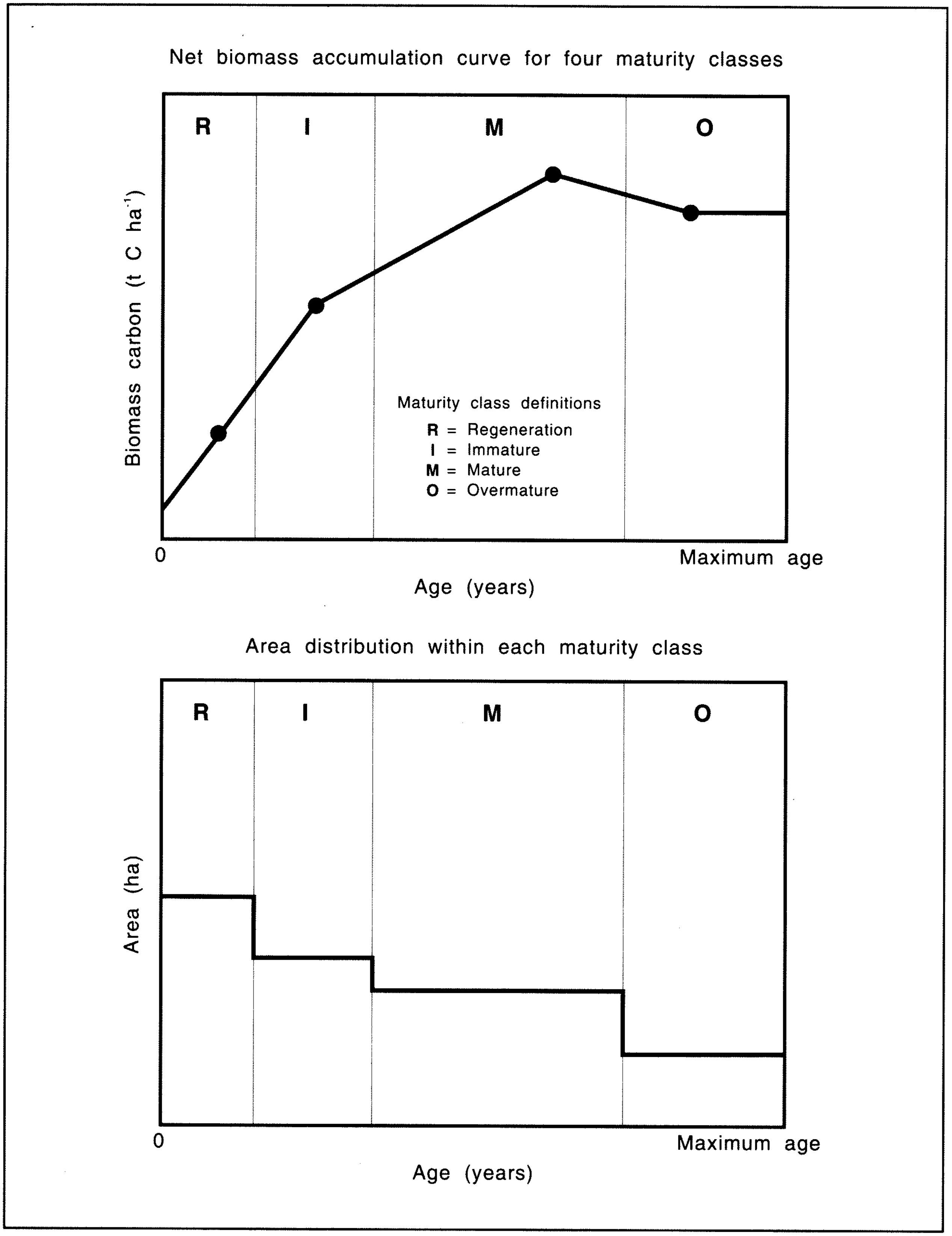


Figure 7. Example of a net biomass accumulation curve, as derived from biomass data for four maturity classes (upper graph); within each maturity class, the area is assumed to be distributed evenly (lower graph).

Forest areas not classified by maturity class (those in maturity class "undetermined") were distributed evenly throughout the full range of ages defined by the lower bound of the regeneration class and the upper bound of the overmature class.

Approximately 1% of the forest area in the inventory is classified as uneven-aged forest. The area of uneven-aged stands was treated similarly to that of unclassified stands because of the lack of data on the C dynamics of uneven-aged stands. Therefore, areas classified as uneven-aged forest were assumed to have the C accumulation characteristics of an even-aged forest. Although this is an erroneous assumption, the error introduced is negligible given the small area involved, and an alternative modeling approach is not readily available.

Disturbances

The C budget model recognizes five disturbance types: wildfires, insect-induced stand mortality, clear-cut logging, clear-cut logging with slash burning, and partial cutting. Other disturbance types may be added easily in the future. Each disturbance is characterized by the following: a series of rules describing the area affected annually in each spatial unit; the classifiers in the C budget model that identify areas eligible for disturbance; and the impact of the disturbance on the C pool sizes and fluxes. (For future phases the plan is to attach postdisturbance ecosystem responses—such as land use and productivity changes—as well, but this level of sophistication is not required for the Phase I single-year assessment.)

Areas Affected Annually by Disturbances

A variety of provincial and federal data bases and expert sources were used to determine the area affected annually by each disturbance type (Appendix 1). While the reference year for all estimates is 1986, not all data used in the model refer to that specific year. Details of the data sources are discussed in the following text (see also Appendix 4).

Wildfire: A decision was made to use the 10-year average for the period 1980–1989 because the area burned annually in Canada fluctuates greatly from year to year (B. Stocks, personal communication, May 1990; C. Van Wagner, personal communication, May 1990). The 10-year averages of areas burned annually were allocated to the 41 spatial units (B. Stocks, personal communication, May 1990). A limited sensitivity analysis was performed with different wildfire levels to explore the sensitivity of the model to this disturbance type (see page 47).

Insects: Only insect infestations resulting in stand mortality are explicitly considered in the Phase I model. The effects on stand growth by insect attacks that cause growth reductions are implicitly included in the historic biomass accumulation curves. Changes in pest management or in climatic conditions that might alter endemic pest levels are not addressed in the first phase of this study.

Although there are estimates of the area defoliated annually in most provinces of Canada, stand mortality occurs only in a portion of the area defoliated. The most recent statistics available at the time of this analysis are the estimates of insect-related volume loss from Honer and Bickerstaff (1985) for the period 1977–1981. The same level of insect-related volume loss was assumed for 1986, and this mortality was distributed across the ecoclimatic provinces (with expert assistance—see Appendix 1).

Clear-cut logging: All estimates of logging activities apply to the reference year 1986. Several provincial and federal data sources were used to estimate the areas logged (Appendix 4).

Clear-cut logging with slash burning: Estimates of annual slash burning were provided by Forestry Canada staff (B. Lawson, personal communication, May 1990; B. Stocks, personal communication, May 1990). Logging statistics do not distinguish between areas that are only logged and those that are logged and then slash burned. It was assumed that areas that were slash burned had been clear-cut and logged in the same year, and therefore the slash-burned area was simply subtracted from the estimate of the clear-cut logged area and assigned to the category that included both logging and slash burning.

Partial cutting: Estimates of partial cutting were derived from the same sources as the area estimates for clear-cut logging. Partial cutting cannot, at present, be represented in the model in a way that is entirely satisfactory; partial cutting often generates uneven-aged stands that are not well-represented in the model. Partial cutting does, however, provide input of timber to the forest product sector, and must therefore be represented in the C budget framework. The assumption was made that the C dynamics of areas undergoing partial cutting could be approximated by representing each hectare of partial cutting as 0.5 ha clear-cut and logged and 0.5 ha undisturbed. The C budget model integrates the C dynamics of clear-cut logged areas and undisturbed areas, thus approximating the C dynamics of a partial cutting.

Disturbances within Spatial Units

Most of the provincial and national data bases on disturbances do not identify the location of the disturbances. The Phase I model recognized 41 explicit spatial entities, to which the annually disturbed areas were assigned (as outlined previously and in Appendix 4). Within each spatial entity, a set of simple disturbance rules was used to assign the disturbed area to the various strata present (i.e., combinations of classifiers).

To identify the areas eligible for disturbances, the following criteria were defined for each spatial entity and each of the five disturbance types:

1. for each appropriate classifier (land class, productivity class, stocking, forest type, and site quality), the classifier values eligible for disturbance (e.g., fire may occur in all forest types, but insect-induced mortality may be restricted to the softwood forest type);
2. the minimum and maximum ages eligible for disturbance;
3. the minimum volume of merchantable stem wood biomass that must be present for an area to be eligible for disturbance (it should be noted that volume is used rather than C content);
4. a maximum level of disturbance defined as the proportion of the total area meeting all criteria that may be affected during one simulation time-step; and
5. a scheduling rule for determining the order in which disturbances are applied (two options are available in the Phase I model: evenly distributed throughout all eligible areas, and oldest age classes first).

These eligibility criteria may be applied singly or in combination, depending on the nature of the disturbance. For example, the combination of the minimum age and minimum stand volume criteria ensures that, during simulated harvesting operations, only areas containing adequate amounts of timber are harvested. This is important because the area harvested must provide the forest product sector model with a stream of timber that is consistent with the provincial harvesting statistics.

Some land areas in the C budget model have no biomass values attached (see page 10). To ensure that only areas with biomass values attached would be used in the assessment of disturbance impacts, an arbitrary minimum-volume criterion was set at 1 m^3 ha^{-1} for all disturbance types. This minimum value is larger for harvesting disturbances.

During a model run, all areas eligible for disturbances are identified in the first pass; in the second pass, the actual disturbances are applied to the required fraction of the eligible areas. It is possible to set the eligibility criteria so tightly that the actual annual disturbance exceeds the available area. During the 1986 simulation this occurred for only one spatial unit (Yukon, Cool Temperate ecoclimatic province), in which 11 675 ha more were scheduled for fire disturbance than were available in the inventory. No attempt was made to reallocate the area burned to different spatial units because it represents less than 0.5% of the 10-year-average (1980–1989) size of area burned annually in Canada.

Disturbance Matrices

Disturbance matrices are used in the model to describe the reallocation of C at the time of disturbance. Disturbances can transfer C between ecosystem C pools and from ecosystems to the forest product sector. Some C may also be released into the atmosphere. The model simulates the flux of C associated with disturbances and summarizes the amounts of C released into the atmosphere.

It is important to note that a disturbance may cause fluxes between C pools without releasing C into the atmosphere. For example, logging (without slash burning) moves C from biomass pools to the forest product sector and to soil C pools, but does not necessarily release C directly to the atmosphere at the time of disturbance. The increased amount of C in the soil C pools (and changes in forest floor exposure) result in greater C release from decomposition, but this is simulated in the soils model.

The model recognizes 12 sources and 16 sinks when simulating the immediate effects of disturbances, and it redistributes the C pools according to instructions provided in the disturbance matrices. A disturbance matrix contains 12 rows (sources) and 16 columns (sinks) (Table 5). Each row contains coefficients that quantify the proportions of the C pool moved from the source to the sinks.

The 12 sources in the disturbance matrix include the eight biomass C pools, three soil C pools, and one unused source (for future use). The 16 sinks describe three forms of gaseous C release into the atmosphere (CO_2, CO, and CH_4), the forest product sector release, and the 12 source C pools. Not all combinations of possible C fluxes can occur in reality (e.g., none of the disturbances move C from the soil C pools to the foliage biomass component).

The model structure accommodates one disturbance matrix for each spatial unit and each disturbance type.

Table 5. Example of a disturbance matrix for simulating fire impacts on carbon transfer from sources (rows) to sinks (columns)[a]

	Sinks[b]															
Sources[b]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.197	–[c]	–	–	–	–	–	–	0.099	0.346	0.049	–	0.278	0.028	0.003	–
2	–	0.185	–	–	–	–	–	–	0.093	–	–	–	0.619	0.094	0.009	–
3	–	–	0.194	–	–	–	–	–	0.097	0.194	–	–	0.464	0.046	0.005	–
4	–	–	–	0.196	–	–	–	–	0.196	0.196	–	–	0.361	0.046	0.005	–
5	–	–	–	–	0.197	–	–	–	0.099	0.346	0.049	–	0.278	0.028	0.003	–
6	–	–	–	–	–	0.185	–	–	0.093	–	–	–	0.619	0.094	0.009	–
7	–	–	–	–	–	–	0.194	–	0.097	0.194	–	–	0.464	0.046	0.005	–
8	–	–	–	–	–	–	–	0.196	0.196	0.196	–	–	0.361	0.046	0.005	–
9	–	–	–	–	–	–	–	–	0.520	0.087	0.087	–	0.275	0.028	0.003	–
10	–	–	–	–	–	–	–	–	–	0.752	0.094	–	0.138	0.014	0.002	–
11	–	–	–	–	–	–	–	–	–	–	0.923	–	0.061	0.014	0.002	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] The numbers refer to the proportion of C contained in a source pool that is transferred to a sink pool at the time of disturbance. See Appendix 5 for a listing of additional disturbance matrices.

[b] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[c] Zero values.

Disturbance matrices for wildfire and for clear-cut logging with slash burning differ between ecoclimatic provinces to reflect properly the impacts of these disturbance types. For the three other disturbance types, one matrix is used for each disturbance without regard to ecoclimatic provinces because of a lack of regionally specific data. The C pool sizes differ between and within ecoclimatic provinces and therefore the absolute amounts of C redistributed during disturbances differ as well.

Soils Module

The soils submodel simulates the C dynamics of the three soil C pools that receive C inputs from the eight biomass C pools (Fig. 8). The soil C pools contain soil organic matter, detritus, coarse woody debris, and standing dead trees. Carbon is released from these pools as a result of decomposition or disturbances. Carbon enters the pools through litter fall, tree mortality, and the transfer of biomass during disturbances. The structure of the soils module is necessarily simple; there are insufficient data to support a complex process-oriented model. Despite its simplicity, the model generates patterns of soil C dynamics that match expected patterns, and the simple model structure enables sensitivity analyses of model assumptions and predictions to be conducted easily.

Most of the input data and assumptions used in the model are anchored in the results of studies done in specific ecosystems, within a relatively narrow range of successional stages and disturbance regimes (Agee and Huff 1987; Anderson and Coleman 1985; Edmonds 1984; Gessel and Turner 1976; Grier 1988; Harcombe et al. 1990; Harmon et al. 1986, 1990; McClaugherty et al. 1984; Melillo et al. 1982; Moore 1989; Piene and VanCleve 1978; Turner and Long 1975). Other relevant studies report averages for larger geographic regions (Bray and Gorham 1964; Emanuel et al. 1984; Vogt et al. 1986). In addition to these published references, professional judgment has been used to identify parameter values appropriate to the range of conditions found in Canada (M. Harmon, personal communication, December 1989; A. Trofymow, personal communication, January 1990; O. Hendrickson, personal communication, January 1990).

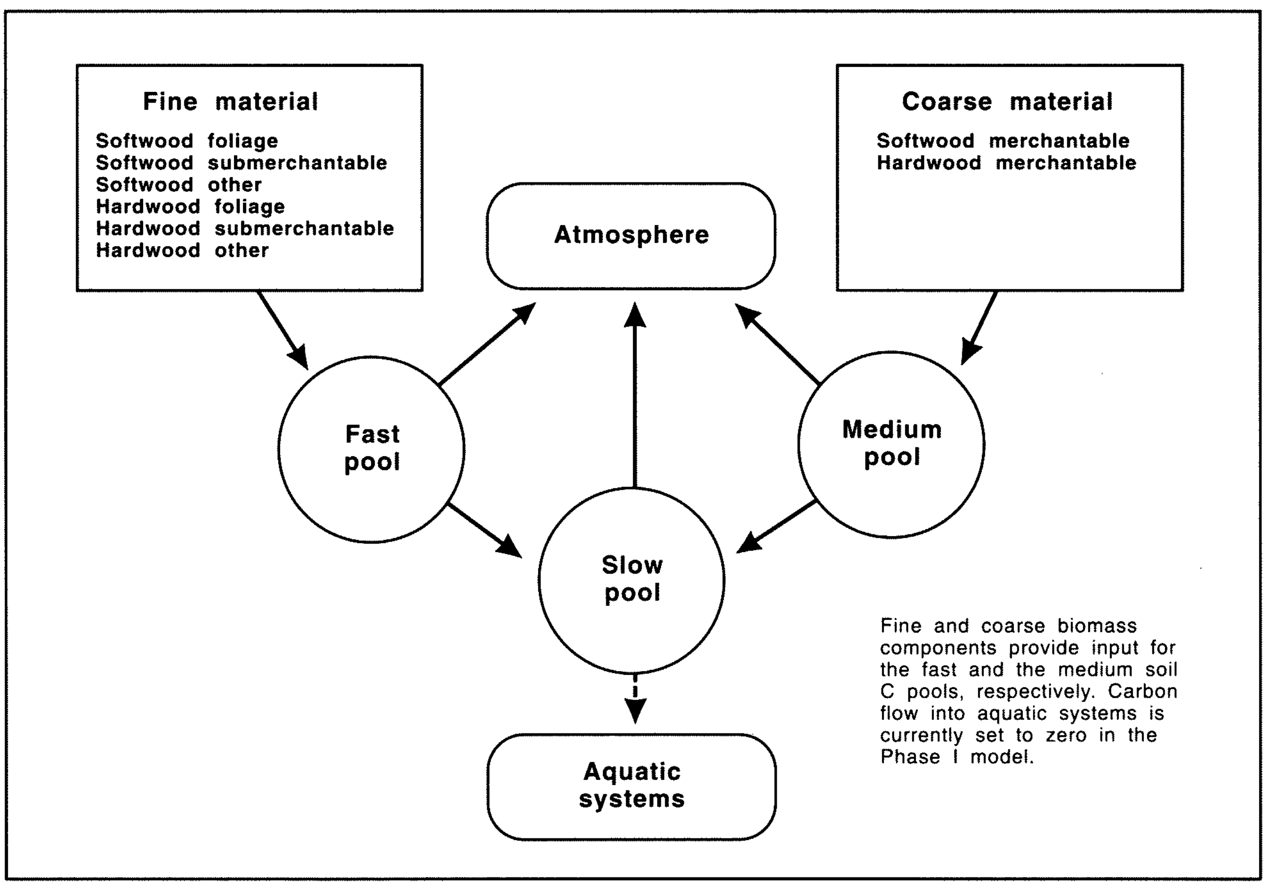


Figure 8. Flow of carbon, as represented in the soils submodel.

Soil C dynamics are simulated only for those areas in the national biomass inventory that have biomass values attached, because, in the model, the dynamics of the soil C pools are coupled to the dynamics of the aboveground stand biomass. The estimates of soil C pools in this study are therefore somewhat smaller than the actual C content in Canadian forest ecosystems. For the analysis of fluxes, the assumption is that the area without soil C data has no net effect on C fluxes: all disturbances are applied to areas with soil C pool data. The C transfer rates to and from soil C pools vary with ecoclimatic province, forest type, disturbance, and aboveground standing biomass. The calculation of both soil C pool sizes and transfer rates is explained in the following sections.

Soil Pools

Forest soils are represented by three C pools that are characterized by different decomposition rates. Within each pool there is a range of decomposition rates for different ecosystems in Canada, with the higher rates (shorter half-lives) occurring in the warmer ecoclimatic provinces. The three C pools are as listed below:

1. A fast (C) turnover pool is characterized by half-lives of 3–20 years and consists of detrital material that is less than 10 cm in diameter. In the soils module this material is assumed to be derived primarily from the following biomass categories (Table 2): softwood foliage; softwood other merchantable; softwood submerchantable; hardwood foliage; hardwood other merchantable; and hardwood submerchantable.

2. A medium turnover pool is characterized by half-lives of 20–100 years and consists of detrital material that is greater than 10 cm in diameter. In the soils module this material is assumed to be derived primarily from the softwood and hardwood merchantable stem categories.

3. A slow turnover pool is typically characterized by half-lives greater than 100 years and consists of the humified soil organic matter in forest soils. A more detailed explanation of this slow pool, as defined in the model, is provided on page 26.

Disturbances can directly change the C content of these pools through C transfer between pools and the atmosphere, and through C input from the biomass pool. These disturbances are quantified by the disturbance matrices (see page 19). Pool sizes are also influenced by detritus inputs, decomposition (with C releases to the atmosphere), and C losses to aquatic systems (currently set at zero due to a lack of data).

Peatlands, characterized by soil organic layers greater than 50 cm thick, are handled separately (see page 10). An attempt was made to incorporate peatland dynamics in the soils module as a set of submerged analogs of the three forest soil pools. Technical difficulties, however, as well as the lack of spatial resolution of the forest and peatland inventories (see page 10), forced abandonment of this approach in the Phase I model.

Calculation of soil pool sizes

Soil pool sizes vary among ecoclimatic provinces and as a function of the disturbance regimes applied, the time since disturbance, and the aboveground biomass dynamics. Soil pool sizes are expressed in tonnes of C per hectare (t C ha^{-1}); this is similar to the approach used for biomass C pools. Direct empirical data on independent pool size estimates were unattainable for the 41 spatial units in the model, and soil C data probably do not exist for all spatial units or for the three soil C pools. Soil C pool sizes were therefore derived through simulation, taking into account observed average pool sizes, decomposition rates, and the impacts of disturbances and stand biomass dynamics.

Soil C dynamics are simulated by a three-pass process. During each pass, the biomass and soil C dynamics are simulated from stand age zero (immediately after disturbance) to the maximum age encountered for a particular combination of forest type and ecoclimatic province (120–260 years; see Appendix 3).

On the first pass, initial conditions are established, and fast and medium soil pool sizes are calculated on the basis of biomass dynamics and decomposition rates. At the end of the first pass, the five disturbances are applied to the soil C pools to establish starting conditions for the second pass. On the second pass the decomposition rate of the slow soil C pool is calculated, and after the second pass the disturbances are applied again. On the third pass, starting conditions and decomposition rates for all soil C pools are available, and look-up tables describing the postdisturbance soil C dynamics for each of the five disturbance types are generated for subsequent use by the main integration module.

The following procedure was adopted for those areas for which biomass C dynamics are simulated in the model. For each of those areas the sequence of nine steps was repeated with each of the five disturbance regimes:

1. The fast and medium C pool sizes are initially set to zero.

2. The soils submodel (described below) is used to simulate the C dynamics of the fast and medium C pools (using a single-year time-step) up to the maximum age specified for that spatial unit (see page 13). Detritus inputs are calculated based on the C dynamics of the aboveground stand biomass, as generated in look-up tables by other components of the C budget model (see page 14). The dynamics of the slow C pool are ignored on the first pass.

3. The disturbance is applied and the three soil C pool sizes are altered according to the disturbance matrix specific to each disturbance type (see page 18).

4. The soil C pool starting values for the second pass are set as follows: the fast and medium pool sizes are those resulting from Step 3; the slow soil C pool is set to a value determined from the Oak Ridge National Laboratory soil C data set (Zinke et al. 1986). (See Table 6 for a summary of starting conditions for the slow C pool.)

5. A second pass of the soils model is performed (as described in Step 2). On the second pass the decay rate of the slow C pool is set to zero, and thus this pool gradually increases as a result of C inputs from the decomposing fast and medium C pools.

6. After the second pass the annual C loss for the slow C pool is calculated. The rate is set to ensure that no net change takes place over the simulated period (see page 13).

7. The disturbance is reapplied and soil C pool sizes are again altered according to the disturbance matrix specific to each disturbance type (see page 18).

8. On the third pass of the soils module the fast, medium, and slow C pools are updated for annual intervals. In this final simulation the postdisturbance starting values (Step 7) and the annual C loss of the slow C pool (Step 6) are used.

9. The size of the soil C pools and their rates of change at each age interval are stored in look-up tables (see page 5).

Decomposition Rate

Fast and medium soil pool decomposition

Very few data exist upon which to develop empirical relationships that represent organic matter decomposition in ecosystems as diverse as those covered by this study. Decomposition rates for this study were derived

Table 6. Initialization values for the slow soil carbon pool are the average soil carbon contents for the eleven ecoclimatic provinces[a]

Ecoclimatic province	Soil carbon content ($kg\ m^{-2}$)	Sample size (n)[b]	Standard error of the mean
Arctic	17.1	12	4.7
Subarctic	33.8	9	9.6
Boreal West	11.8	51	1.5
Boreal East	11.8[c]	–[d]	–
Cool Temperate	9.2	3	1.1
Moderate Temperate	8.4	2	2.7
Grassland	4.9	1	–
Subarctic Cordilleran	33.8[e]	–	–
Cordilleran	13.8	20	3.0
Interior Cordilleran	26.7	4	11.3
Pacific Cordilleran	12.7	15	3.0

[a] Data from Zinke et al. (1986) were located on the map of ecoclimatic provinces, using latitude and longitude references.

[b] Seven data points indicating C contents from 100 to 450 kg C m^{-2} have been excluded because they are assumed to represent peatland C content.

[c] The same data have been used for Boreal East and Boreal West.

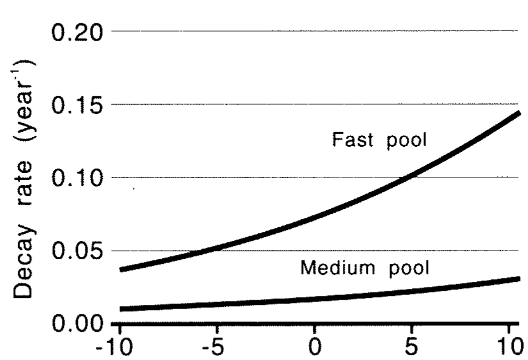
[d] Not applicable.

[e] The same data have been used for Subarctic Cordilleran and Subarctic.

using simple relationships between decomposition rates and the soil C pools (fast and medium), mean annual temperature, forest type, and stand development stage.

Conceptually, three decay rate parameters are recognized for each of these two C pools: a minimum decay rate, a maximum decay rate, and a slope parameter. The minimum decay rate is a function of mean annual temperature and forest type. As forest stands reach the ecosystem specific maximum stand biomass, the soil C pools are assumed to approach the minimum decay rate. The maximum decay rate occurs when aboveground standing biomass is zero (i.e., following disturbances). The maximum decay rates are 1.25–2 times the minimum decay rate. At any point in forest stand development, the soil C pools decay at a rate between the minimum and maximum decay rates.

The minimum decay rates of the fast and medium C pools in the softwood forest type of the Moderate Temperate ecoclimatic province (having a mean annual temperature of 7.3°C) are used as reference decay rates. Using empirical data (M. Harmon, personal communication, December 1989; A. Trofymow, personal communication, January 1990), those rates were determined as 0.119 yr^{-1} and 0.024 yr^{-1} for the fast and medium pools, respectively. For other ecoclimatic provinces, the minimum decay rates were calculated as a function of mean annual temperature (Fig. 9) and the reference decay rates. The functional relationship assumes a Q_{10} of 2 (i.e., for every 10°C temperature increase, decomposition rates double). The mean annual temperature and minimum decay rates for all 11 ecoclimatic provinces are listed in Table 7.



Each curve passes through the reference decomposition rates for the moderate temperate ecoclimatic province (having a mean annual temperature of 7.3°C).

Figure 9. Minimum decay parameter for the fast and medium soil pools as a function of mean annual temperature.

Minimum decay rate parameters for the other two forest types are derived from those of the softwood forest type by assuming that, within each ecoclimatic province, the minimum decay rates for the hardwood forest type are 1.5 times those for the softwood type, and the minimum decay rates for the mixedwood forest type are calculated as the arithmetic averages of the softwood and hardwood minimum decay rates.

Maximum decay rate parameters of the two C pools for the softwood forest type are assumed to be 1.25 times the minimum decay rates. For the hardwood forest type, maximum decay rates are twice the minimum decay rates, and for the mixedwood forest type they are calculated as the arithmetic averages of the softwood and hardwood maximum decay rates.

The actual decay rate is assumed to be a function of stand development as expressed in the ratio of standing biomass to maximum potential standing biomass (Biomass/MaxBiomass). The latter is defined as the maximum value of the site-specific biomass accumulation curves (see page 11). Biomass/MaxBiomass varies from near zero after a severe disturbance to 1.0 as the stand approaches maximum stand biomass. In some cases the ratio may decline again during the stand break-up phase. This biomass ratio is assumed to capture the effects of stand opening following disturbance, varying litter quality (lignin-to-nitrogen ratios), and forest succession on detrital decomposition rates. As aboveground biomass increases following disturbance, the decay rate declines exponentially from the maximum decay rate parameter toward the minimum decay rate parameter (Fig. 10), as described in Eq. [1].

$$[1]\quad DecayRate = MinDecay + (MaxDecay - MinDecay)\, e^{-b(Biomass/MaxBiomass)}$$

where:

MaxDecay = decomposition rate parameter for the soil pool in the absence of any forest biomass (i.e., Biomass = 0),

MinDecay = decomposition rate parameter for the soil pool at the point where the forest biomass equals the maximum possible aboveground biomass for the site (Biomass = MaxBiomass),

Biomass = forest biomass in the current simulation time-step,

Table 7. Parameters defining the decay rates of fast and medium soil carbon pools

	Ecoclimatic province										
Parameter	Arctic	Subarctic	Boreal West	Boreal East	Cool Temperate	Moderate Temperate	Grassland	Subarctic Cordilleran	Cordilleran	Interior Cordilleran	Pacific Cordilleran
Mean annual climate parameters											
Temperature (°C)	–10.8	–5.0	2.4	–0.6	4.5	7.3	2.9	–7.5	–0.7	6.3	4.6
Precipitation (cm)	17.0	62.3	98.3	45.4	93.3	90.9	44.5	37.5	59.2	61.8	91.4
Minimum decay rate (yr^{-1})											
Fast soil C pool											
Softwood	0.033	0.051	0.084	0.068	0.097	0.119	0.088	0.043	0.068	0.111	0.099
Hardwood	0.051	0.076	0.127	0.103	0.147	0.179	0.131	0.064	0.103	0.167	0.148
Mixedwood	0.043	0.063	0.105	0.085	0.123	0.148	0.109	0.053	0.085	0.139	0.123
Medium soil C pool											
Softwood	0.007	0.011	0.017	0.013	0.020	0.024	0.017	0.008	0.013	0.023	0.020
Hardwood	0.011	0.016	0.025	0.021	0.029	0.036	0.027	0.013	0.021	0.033	0.029
Mixedwood	0.008	0.013	0.021	0.017	0.025	0.031	0.023	0.011	0.017	0.028	0.025
Maximum decay rate (yr^{-1})											
Fast soil C pool											
Softwood	0.043	0.063	0.105	0.085	0.123	0.148	0.109	0.053	0.085	0.139	0.123
Hardwood	0.101	0.152	0.253	0.205	0.293	0.356	0.263	0.128	0.204	0.332	0.295
Mixedwood	0.069	0.103	0.172	0.140	0.199	0.241	0.177	0.087	0.139	0.225	0.200
Medium soil C pool											
Softwood	0.008	0.013	0.021	0.017	0.025	0.031	0.023	0.011	0.017	0.028	0.025
Hardwood	0.020	0.031	0.051	0.041	0.059	0.072	0.053	0.025	0.041	0.067	0.060
Mixedwood	0.013	0.021	0.035	0.028	0.040	0.049	0.036	0.017	0.028	0.045	0.040

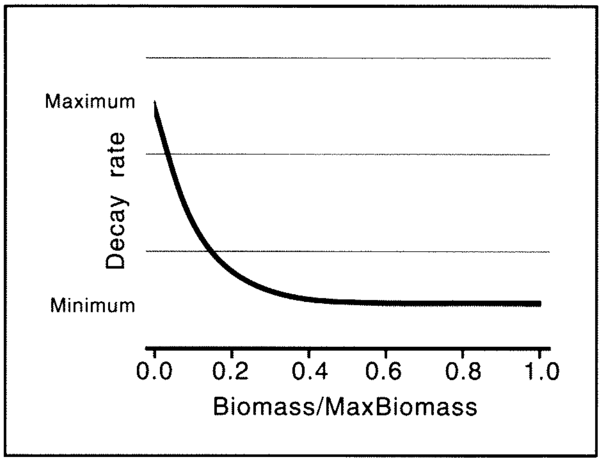


Figure 10. Decay rate as a function of stand development, as described in the ratio of stand biomass to the potential maximum biomass.

MaxBiomass = maximum possible forest biomass for the spatial unit, as determined from the site-specific biomass-over-age curves (see page 11), and

b = slope parameter describing the rate of exponential decline (current default value = ln 0.0001 = 9.21).

The value for the parameter b in Eq. [1] was chosen so that the decay rate is at the midpoint between the minimum and maximum decay rate parameters when the aboveground biomass has reached about 7.5% of the maximum value during stand development (Fig. 10). The regrowing vegetation at that time is assumed to provide sufficient shade to reduce the energy input to the forest floor and therefore reduce decomposition rates. The values for the various decomposition rates used in the submodel are summarized in Table 7.

Slow pool decomposition

The release of C from the slow soil pool is simulated using an approach fundamentally different from that of the other two soil pools. Defined as a pool with C retention times typically greater than 100 years, slow pool C release is expected to exhibit little net change over the natural life of a forest stand. Furthermore, the slow pool decomposition rate is assumed to be independent of both the amount of stand biomass and the time since last disturbance. The approach used in this study assumes that the slow soil C pool is in effectively steady state when stand disturbances occur at intervals of 120 to 260 years (depending on the ecoclimatic province). If stand disturbances occur at more frequent intervals, the size of the slow C pool may progressively deviate from the initial starting condition because of the changes in organic matter input.

The annual C loss from the slow pool is calculated in several steps (see page 22). The initial slow soil C pool size is constrained by observed data for each ecoclimatic province. The soils submodel then performs a simulation up to the maximum stand age (120–260 years) for each ecoclimatic province, adding the C inputs from the fast and medium pools to the slow C pool. During the second pass simulation, the slow pool decay rate is set at zero, allowing all C transfer from the fast and medium C pools to accumulate. At the end of the second pass of the soils submodel, the annual decomposition C loss from the slow pool is calculated as the total C accumulation divided by the time period simulated. When this annual C loss from the slow soil C pool is used during the third pass of the simulation, the slow soil C pool reaches its starting value at the end of the simulated time period.

The annual C loss from the slow C pool, as calculated in the submodel, is constant; it is also independent of the stand biomass, unlike the decomposition rates of the fast and medium pools. A constant annual C loss from the slow soil C pool implies a variable decomposition rate, however, because the size of the slow C pool changes as inputs from the fast and medium pools change with stand development.

Soil Carbon Pool Inputs

In forest ecosystems, all C in forest floor and soil organic matter was initially taken up through plant photosynthesis and then transferred to the soil as detritus. In the Phase I model, therefore, all C inputs to the fast and medium soil C pools originate with the biomass C pools. Inputs to the slow soil C pool, which represents humified soil organic matter, are transferred only from the fast and medium soil C pools.

Conceptually, biomass C inputs to the soil C pools are derived from three processes: annual turnover of biomass (e.g., foliage litter fall, mortality of fine roots, or death of suppressed trees), the mortality of trees reflected by a net decline of stand biomass, and disturbances. The aboveground stand biomass dynamics are described in net C accumulation curves (see page 11). Each biomass C pool has an annual litter fall rate that determines the annual detrital input to the fast and medium soil C pools. The annual litter fall rates cannot be directly inferred from the biomass accumulation curves because these curves represent only the net changes in biomass. Biomass turnover rates are therefore defined in the soils module in order to simulate annual C inputs to the soil C pools.

Net increases in the biomass C pools represent removal of C from the atmosphere. Net decreases of C in the biomass C pool in the absence of fire are, however, not directly released to the atmosphere, but represent a transfer of C to the soil C pools (through litter fall and stem mortality) or to forest product pools. The soils submodel therefore also monitors the aboveground biomass dynamics and accounts for net reductions in aboveground biomass as input to the soil C pools. This input is in addition to the annual detrital turnover and disturbance inputs.

Inputs to the slow soil carbon pool

Carbon leaving the decomposing fast and medium soil pools either enters the slow pool (i.e., humified soil organic matter) or is released to the atmosphere (Fig. 8). In the Phase I model, it is assumed that a constant 17% of the C leaving the fast and medium soil pools is transferred to the slow pool, and that the remaining 83% is released to the atmosphere in the form of CO_2. The implications of changes to this assumption are explored in a sensitivity analysis described on page 49.

Inputs to the medium soil carbon pool

The medium soil C pool receives input from merchantable stem wood (including bark) and other merchantable biomass components (stumps, tops, and branches of trees of merchantable size) from both the softwood and hardwood components of stands. For a given ecoclimatic province, the rate of input is a fixed proportion of the existing biomass C pool of these components (Table 8).

In addition to the input from biomass turnover, C is added to the medium C pool if the total biomass C pool decreases during a simulation time-step. This input accounts for C transfer to soil pools during stand break-up in the overmature phase. The additional C input is calculated from the net reduction in the total biomass pool and the proportion of biomass in components that provide input to the medium soil C pool. The total annual C input to the medium soil C pool is calculated as follows:

$$[2]\ MedInput = (MedInRate \times Biomass + LossBio) \times BioProp$$

where:

MedInput = C input to the medium C soil pool per time-step (t C ha^{-1} yr^{-1}),

MedInRate = input rate parameter (specific to the ecoclimatic province) (yr^{-1}),

Biomass = total size of all biomass C pools (t C ha^{-1}),

LossBio = net reduction of Biomass in the previous time-step (provided the reduction is greater than zero) (t C ha^{-1} yr^{-1}), and

BioProp = proportion of Biomass in the eligible components (i.e., the merchantable stem wood and other merchantable biomass components of both the softwood and hardwood stand biomass).

Inputs to the fast soil carbon pool

Inputs to the fast soil C pool are simulated using the same conceptual approach as with the medium pool; however, the fast soil C pool receives input from several additional biomass components. The C inputs to the fast pool are calculated as follows:

$$[3]\ FastInput = FineInput + SubMerchInput$$

where:

FastInput = total C input to the fast C pool,

FineInput = input from foliage litter fall and fine-root detritus, and

SubMerchInput = input from submerchantable components of the aboveground biomass.

Fine-root and foliage detrital inputs are linked in the model by root-to-foliage ratio parameters (based on their C masses). These parameters take on different values for hardwoods and softwoods and are specific to each ecoclimatic province:

$$[4]\ FineInput = \{foliage\ input\} + \{fine\ root\ input\}$$

$$= (1 + rfSW) \times SWFolRate \times (Biomass + LossBio) \times BioProp_{sf} + (1 + rfHW) \times HWFolRate \times (Biomass + LossBio) \times BioProp_{hf}$$

where:

rfSW = root-to-foliage ratio for the softwood component,

rfHW = root-to-foliage ratio for the hardwood component,

SWFolRate = proportion of softwood foliage in annual litter fall,

Table 8. Parameters defining maximum annual input rates for fast and medium soil carbon pools

Parameter	Ecoclimatic province										
	Arctic	Subarctic	Boreal West	Boreal East	Cool Temperate	Moderate Temperate	Grassland	Subarctic Cordilleran	Cordilleran	Interior Cordilleran	Pacific Cordilleran
	Input rate[a]										
Fast pool inputs											
Inputs from foliage											
Softwood (SWFolRate)	0.050	0.050	0.100	0.100	0.150	0.150	0.150	0.100	0.100	0.100	0.150
Hardwood (HWFolRate)	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900
Other detrital input											
Softwood (SWSMRate)	0.030	0.030	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Hardwood (HWSMRate)	0.030	0.030	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Medium pool inputs (MedInRate)	0.006	0.006	0.005	0.005	0.0067	0.0077	0.006	0.006	0.0045	0.0045	0.006
	Fine root-to-shoot foliage ratio										
Softwood (rfSW)	0.007	0.007	0.007	0.007	0.015	0.016	0.016	0.007	0.007	0.015	0.016
Hardwood (rfHW)	0.005	0.005	0.005	0.005	0.009	0.013	0.013	0.005	0.005	0.009	0.013

[a] The numbers refer to the proportion of biomass carbon that is transferred annually to the fast and medium soil carbon pools.

HWFolRate = proportion of hardwood foliage in annual litter fall,

Biomass = total size of all biomass C pools,

LossBio = net reduction of Biomass in the last time-step (provided the reduction is greater than zero),

$BioProp_{sf}$ = proportion of Biomass in the softwood foliage component, and

$BioProp_{hf}$ = proportion of Biomass in the hardwood foliage component.

The variable SubMerchInput accounts for the detritus input from the vegetation biomass of submerchantable size:

$$[5]\ SubMerchInput = SWSMRate \times (Biomass + LossBio) \times BProp_{ss} + HWSMRate \times (Biomass + LossBio) \times BProp_{hs}$$

where:

SWSMRate = annual litter fall rate of the softwood submerchantable biomass component,

HWSMRate = annual litter fall rate of the hardwood submerchantable biomass component,

Biomass = total size of all biomass C pools,

LossBio = net reduction of Biomass in the last time-step (provided that the reduction is greater than zero),

$BProp_{ss}$ = proportion of Biomass in the softwood submerchantable component, and

$BProp_{hs}$ = proportion of Biomass in the heartwood submerchantable component.

The default model values for the parameters rfSW, rfHW, SWFolRate, HWFolRate, SWSMRate, and HWSMRate are listed in Table 8.

Although the equations specifying detrital inputs from forest biomass distinguish between softwood and hardwood biomass inputs, the soil C pools themselves do not make such a distinction. Decomposition rates do, however, vary with forest type (softwood, hardwood, or mixedwood) and ecoclimatic province (see page 23).

Example of Soil Submodel Behavior

Examples of the soil submodel behavior for a productive, stocked, softwood forest of site class 3 (high) in the Eastern Boreal ecoclimatic province are shown in Figure 11.

The five graphs represent the five disturbance types simulated in the model: wildfire, insect mortality, clear-cut and burn, clear-cut, and partial cut. The biomass curves are the same in all five cases because postdisturbance biomass dynamics are assumed to be independent of disturbance in the Phase I model (see page 11).

To understand the C dynamics of the partial cut disturbance type, it must be remembered that partial cutting in the model is approximated by treating 50% of the area as completely logged and 50% as undisturbed. This approach is required because the carbon budget model does not explicitly represent uneven-aged stands (see page 18). The dynamics shown in Figure 11 are only those of the cut portion of the stand. For example, as explained earlier, partial cutting of 50% of the biomass in a 10-ha, 100-year-old stand is simulated by assigning the C dynamics of the partial cut to only 5 ha (Fig. 11). The remaining 5 ha continue to grow as a 100-year-old stand. The model integrates the C fluxes over the 10 ha, thus approximating the C dynamics of a partially cut stand.

The simulation results of the soil submodel are consistent with expected and observed behavior of forest soils following disturbance. The soil C pool levels at the youngest age reflect the immediate effects of the disturbance itself: predisturbance C pools have been reallocated using the disturbance matrices (see page 19; Appendix 5). The initial fast soil C pool size is smallest for wildfire disturbance and largest for clear-cutting and partial cutting. This reflects the reduction of the fast soil C pool believed to result from wildfire and the addition of material to the fast soil C pool during harvesting. The medium soil C pool has a low initial size following cutting because much of the merchantable stem wood biomass has been removed from the site. In contrast, the larger initial size of the medium soil C pool following insect-induced mortality is caused by the simulated inputs of large-size (merchantable) timber. The subsequent decline of the initially large, medium soil C pool in this scenario is due to its gradual decomposition.

The decline of the fast soil C pool during the first 40 years of postdisturbance forest development reflects the effects of the increased soil decomposition rate in the more-open stand conditions (i.e., low ratio of Biomass to MaxBiomass) (Fig. 9). It also reflects the reduced biomass input during the early stages of stand development (Eq. [2]). Similar (though less dramatic) postdisturbance declines of the medium soil C pool are also observed. The changes are smaller in the medium soil C pool because of the lower decomposition rates (Table 7). The declines of the fast and medium soil C pools similarly manifest themselves in small changes in the slow soil C pool later in the simulation.

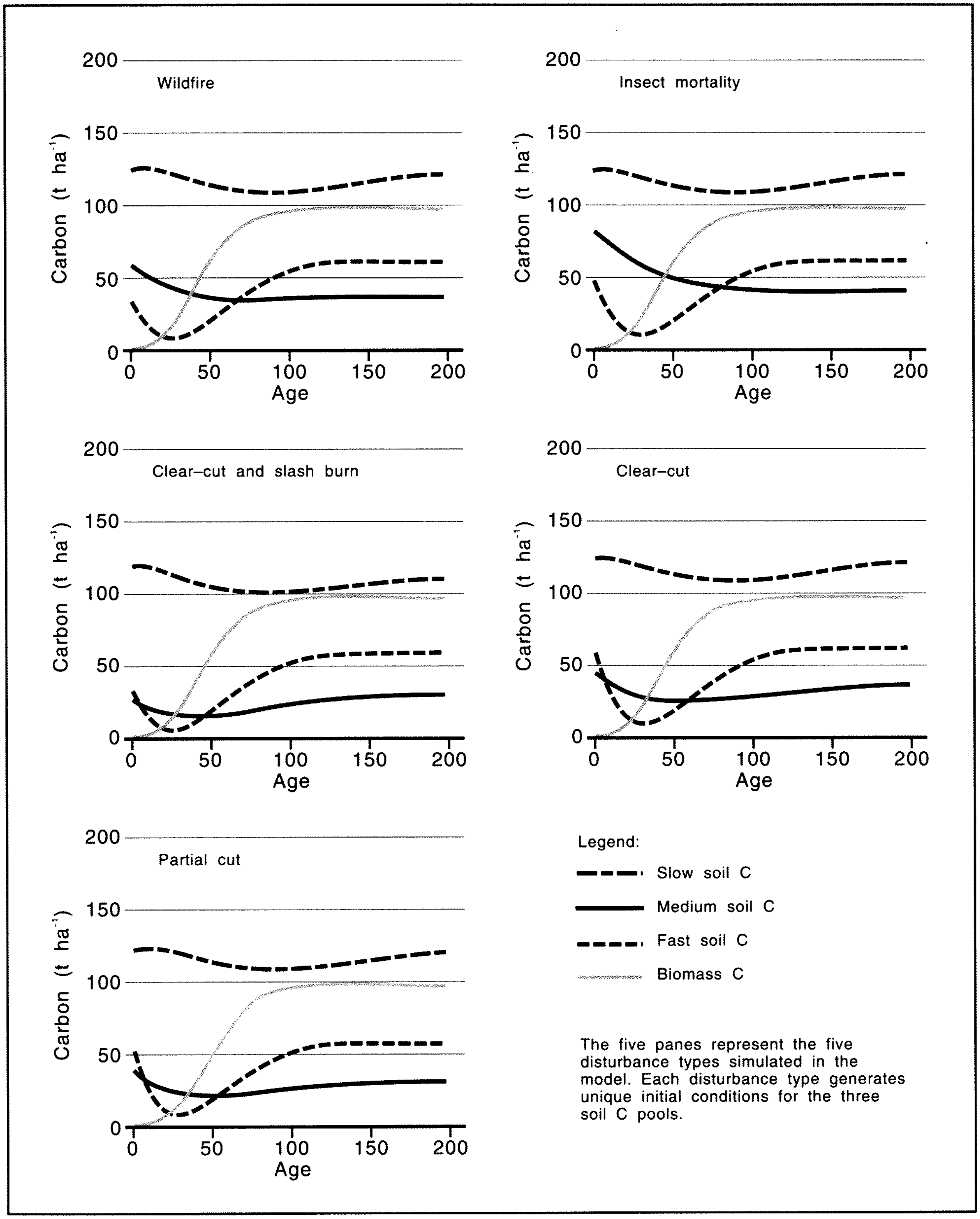


Figure 11. Example of biomass and soil carbon dynamics simulated by the carbon budget model.

Forest Product Sector Submodel

The forest product sector submodel simulates the utilization and disposal of the wood harvested in the main C integration module (Fig. 2) and estimates the rate and form in which the C contained in this wood is released to the atmosphere. The model represents a series of processing steps used to convert the harvested biomass into various forest products (including bioenergy). The Phase I model simulates the C emissions associated with the burning of woody biomass, but it accounts for neither the energy replacement (fossil fuel) nor the energy required for the transportation and processing of forest biomass. Energy use requirements and energy substitution potential in the forest sector will be addressed in a future phase of this study.

The forest product sector module uses data on the biomass harvested in each spatial unit of the C budget model. Harvested biomass is allocated to softwood saw timber, hardwood saw timber, pulpwood, or fuelwood (Fig. 12), and various end uses (Fig. 13). Biomass in each of the harvest categories is tracked through a series of industrial processes that differ in conversion efficiency and the amounts and types of by-products.

Three C pools are generated for forest products: construction lumber, other lumber, and pulp. In each of these pools, C inputs are tracked through annual age classes. A C retention curve (CRC) is associated with each of these forest product pools. These CRCs are used to describe the proportion of C that leaves each age class of a particular forest product pool each year. The forest product sector module also accounts for C (originating from forest biomass) deposited in landfills by generating a fourth forest product pool. For each of the four forest product pools, a CRC is used to describe quantitatively the C release from that pool (Fig. 14).

Any C leaving a forest product pool can meet one of five fates (Fig. 13): both decomposition and burning (for energy or waste) immediately release C into the atmosphere; product recycling is assumed to return the C to the first age class of the forest product pool; and transfers to a landfill lead to C release through gradual decomposition. The rate and form (CO_2, CO, and CH_4) of C loss to the atmosphere depend on the type of forest product. In particular, C is lost from landfills in gaseous forms (CO_2 and CH_4) at a rate described by the CRC specific to landfills. The values selected for different parameters used in the forest product sector module are described in the following text. Detailed descriptions of all parameters used are given in the data tables in Appendix 6.

Although the model results reported in this study are based on the simulation of the C dynamics of a single year, forest products harvested before the reference year contribute to the C emissions to the atmosphere during that year. Past harvesting rates and a simulation of past forest product processing were used in the model to develop the C content and age-class structure of the four forest product C pools. In any given year, a large fraction of the C released to the atmosphere by the forest product sector is derived from wood harvested in previous years. Hence, C emissions from the forest product sector have some inertia in responding to changes in harvesting and other policy decisions.

The forest product sector module provides a bookkeeping framework that monitors the fate of the harvested biomass C. The following general factors are considered in this process.

Cull losses: Of the wood removed from harvested areas, a certain proportion is not suitable for processing due to rot and other factors. These losses and the fate of the wood that they represent must be accounted for in the C budget. Cull that occurs in the forest is accounted for in the disturbance matrices (see page 19), which designate that only a portion of the available merchantable stemwood leaves the stand. Additional cull losses during forest product processing are accounted for as by-products and waste in the forest product sector module (Fig. 12).

Transportation: It is important to consider transportation for two reasons: the transportation process consumes energy (with associated CO_2 emissions), and there can be losses associated with the transportation of wood, such as logs sinking from log booms. Although losses from log booms may at one time have been around 5%, these losses have been greatly reduced with the widespread use of bundle booms, and are therefore ignored in the Phase I model.

Processing: Logs are processed into a variety of products, such as lumber, tissue paper, and plywood. The previously discussed C transfers are shown in Figure 12. The processing steps for the different product types are described in more detail in the following text. Additional factors considered include the consumption of energy, the production of waste that may go into landfills, the production of secondary products (such as chips for pulp), the burning of wood waste that produces CO_2, CO, and CH_4, and the generation of energy from the burning of waste.

Product lifetimes: The duration for which a particular product remains in its primary use is described in the CRCs. These curves and the fate of forest products

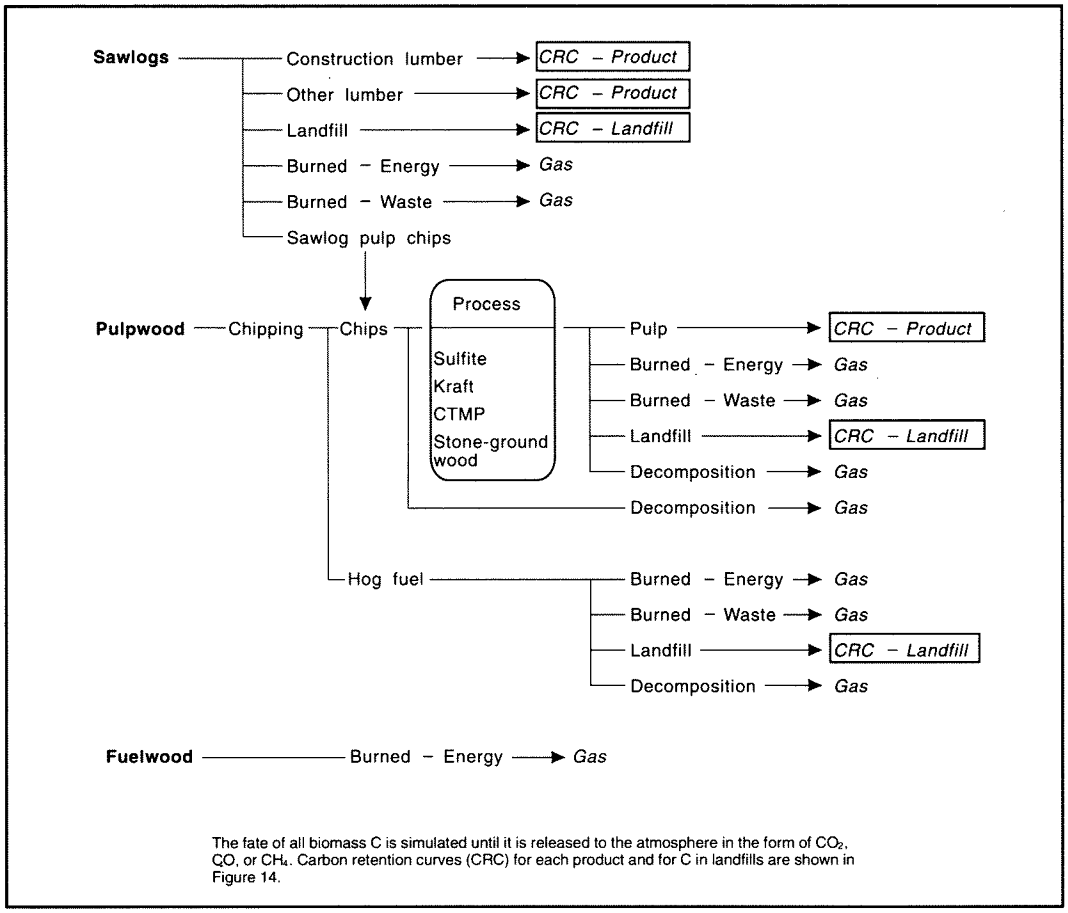


Figure 12. Overview of the processes represented in the forest product sector model.

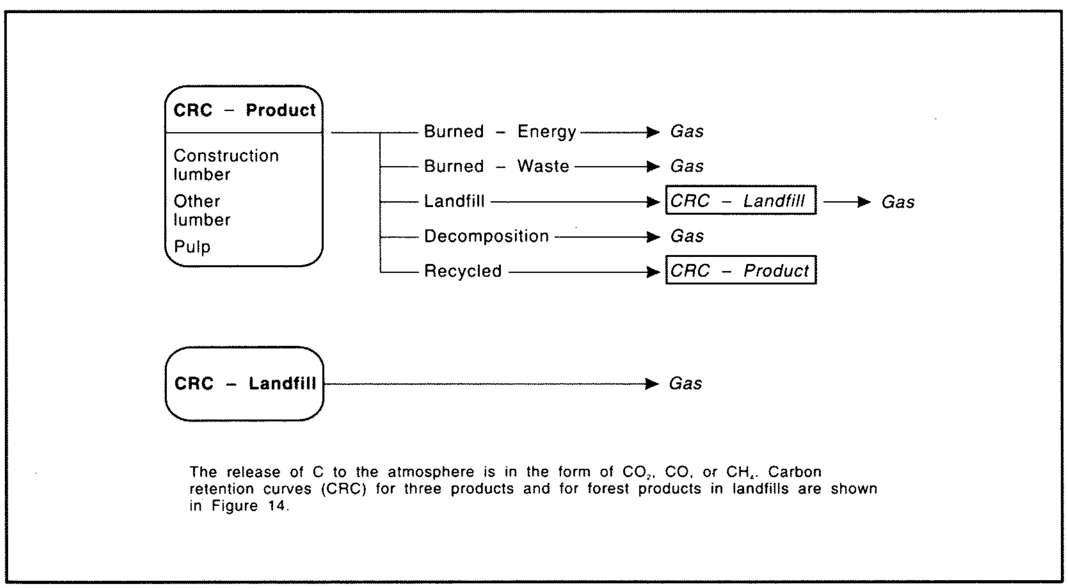


Figure 13. Overview of the fate of carbon in forest products and landfills.

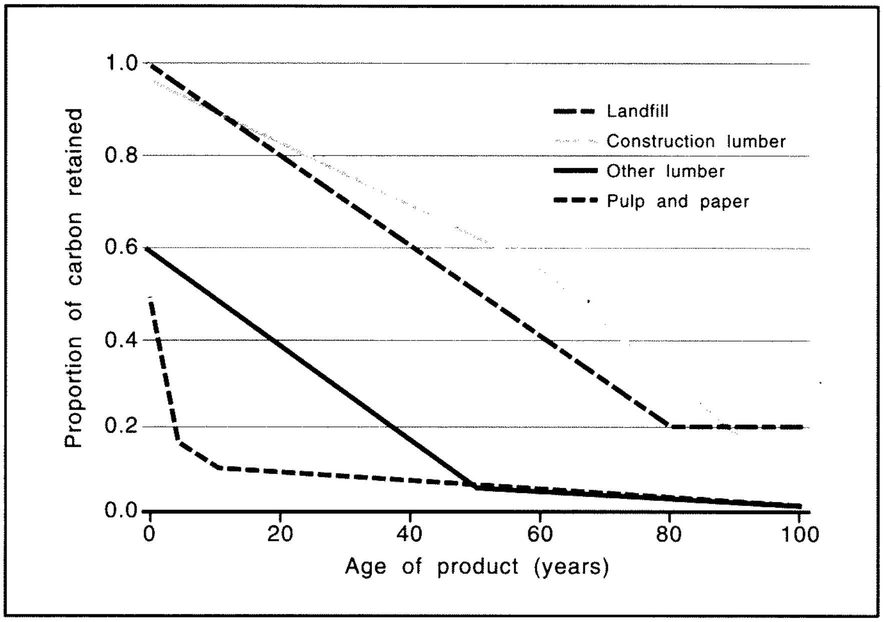


Figure 14. Carbon retention curves for three forest product categories (construction lumber, other lumber, and pulp products) and for forest products discarded in landfills.

fuelwood production for all years was set to zero, because the figures were not easily extracted from the available data. The Council of Forest Industries of British Columbia provided information on volume harvested (1922–1969) in a table entitled "Canada Log Production, Softwood and Hardwood Combined, Total Logs, Bolts, Pulpwood, Fuelwood and Misc. Roundwood." This source was used to compile volume harvesting statistics for the period 1947–1969. The average distribution of production into the four categories (logs and bolts, pulpwood, fuelwood, and other roundwood) was calculated for the years 1970–1974 from Forestry Canada (1989) data. The same partitioning was then applied to pre-1970 production totals.

after they leave the primary-use category are described in the previous text.

Data Sources

Data for the forest product sector model were obtained at the C budget workshop (Appendix 1) and from published sources. Wood volumes harvested during 1970–1986 were compiled from Forestry Canada statistics (Forestry Canada 1989). This source divides total roundwood production into four categories: logs and bolts, pulpwood, fuelwood, and other roundwood.

The breakdown of roundwood figures into hardwood and softwood figures was available only for British Columbia. For the other provinces, the allocation was assumed to be proportional to that of lumber (lumber breakdown by province and species group; Forestry Canada 1989). British Columbia's pulpwood production figures were provided only in units of 1000 t. To convert to 1000 m^3, a conversion factor of 2.79 was estimated by comparing Ontario's 1970, 1980, and 1986 pulpwood production in units of 1000 t to those in units of 1000 m^3. Estimated pulpwood production was then subtracted from the softwood portion of British Columbia's log and bolt production figures.

British Columbia's fuelwood production figures are included in the roundwood totals; the province's

Forest Products

Harvested biomass is processed into different forest products and by-products (Fig. 12). Parameters partitioning C in the various processing steps, as well as the C retention coefficients described here, are largely based on values determined at the C budget workshop (Appendix 1). Those data represent best-available estimates of the existing condition and are assumed to be valid for 1986. All the parameter values described are located in data files external to the model and can therefore be modified for sensitivity analyses and model refinement. Historical variations in these rates are discussed on page 35. All forest products quantities are expressed in tonnes of C.

Softwood sawlogs and veneer logs

Softwood sawlogs and veneer logs are converted to lumber with an assumed efficiency of 45%. Of the lumber produced, 70% is used for construction and 30% is used as "other lumber," including palettes, trim, and packaging. The by-products from the conversion process fall into three categories, as described by the following parameters:

1. 10% is used in production of panel board (added to the "other lumber" pool);

2. 45% is used for pulp chips; and

3. the remaining 45% is treated as residue, with two-thirds burned as waste, and one-third burned for energy.

Retention curves for construction lumber and other lumber differ (Fig. 14). Five percent of construction lumber is assumed lost during the first year due to fitting and shaping during construction. Thereafter, the decline in the retention curve slows, with C loss reaching 50% for construction lumber at 60 years. The decline continues so that only 5% of the original lumber is assumed to remain in its primary use at 100 years.

Wood in the "other lumber" category is lost more rapidly from its primary use. In the first year, 40% of the C is lost from "other lumber" to reflect use in nonreusable products, such as palettes and packaging. This is followed by a slower decline, so that after 50 years only 5% of the C originally classified as "other lumber" remains in its primary use.

Construction lumber and other lumber leaving primary use are currently assigned to destinations according to the following proportions: 85% is sent to landfill sites, 3% is burned as waste, 2% is burned to generate energy, 5% decomposes, with C released to the atmosphere as CO_2 and CH_4 (in equivalent units), and 5% is recycled.

Recycling is represented in the model simply by adding the recycled amount to the first age class of the appropriate C pool that contains the current year's production. In the next phase of this study, energy consumption and C losses associated with product recycling will also be considered.

Hardwood sawlogs

In the model, hardwood sawlogs are converted to "other lumber," pulp chips, and residues. Although aspen can be converted to panels and waferboard, which are considered construction lumber, the harvest data do not distinguish between hardwood species. Therefore, only one hardwood category was used in the model.

The fate of hardwood sawlogs is described by the following parameters: 30% is used for non-construction lumber, 35% is used for pulp chips, and 35% is used for residue. Of the residue, 20% is burned for energy and 80% is burned as waste.

The retention curves for these hardwood products are assumed to be the same as those for the softwood saw lumber.

Hardwood and softwood pulp logs

Pulp logs are converted to chips with an assumed efficiency of 85%. The residue from this process consists of bark and fine materials that may be either burned or placed in landfills. Chips from this process and the saw chips from lumber mills are stored until processing. Storage entails a further loss through decomposition (5%).

Logs and chips are processed for pulp by one of four possible processes: sulfite cooking, kraft processing, chemithermomechanical pulping (CTMP), and stone-ground wood pulping. The first two of these processes have relatively low conversion efficiencies (50 and 40%, respectively) and their residues are largely burned and released to the atmosphere as CO_2. The conversion efficiencies of CTMP and stone-ground wood pulping are much higher (85 and 95%, respectively). Their residues fall into two categories: those that decompose rapidly and those sent to landfills. Although it is recognized that logs, not chips, are used as the input to the stone-ground wood process, the approach described above is used to maintain a uniform model structure. In the next phase of this study, the number of processing steps and pulp products used in the model will be increased to reflect more accurately the different processing steps in the pulp and paper sector.

Most pulp-based products do not last as long as lumber, and this is reflected in the retention curves (Fig. 14). Fifty percent are assumed to be lost in the first year, largely due to short-lived products, such as tissue paper and newsprint. The rate of decline then slows so that 15% remains at 5 years and 10% at 10 years. The retention curve thus slowly approaches zero at 100 years, reflecting such long-lived products as books, building papers, and fiberboard.

Of the pulp and paper products leaving the primary use, the model parameters currently assign destinations according to the following proportions: 90% is sent to landfill sites, 2.5% is burned as waste, 2% is burned to generate energy, 0.5% decomposes (with C released to the atmosphere as CO_2 and CH_4), and 5% is recycled.

Fuelwood

Fuelwood is burned for energy, releasing all C to the atmosphere as CO_2. In the Phase I version of the model, there has been no attempt to account for particulate emissions, for the C remaining in charcoal and ashes, or for replacement by fossil fuel energy sources.

Landfills

Decomposition rates in landfills are fairly low and are thought to be approximately 1–2% per year for about 80% of the material stored in them. The remaining 20% of material in landfills is thought to decompose even more slowly, effectively forming a long-term store of C.

Forest product material entering a landfill is assumed to release C in the form of CO_2 in the first year. In the second year, C is released from the landfill in equal proportions of CO_2 and CH_4. In all subsequent years, only CH_4 is released. Methane produced in landfills may be burned for conversion to CO_2. In turn, this process may be used to generate energy, although the energy use and CH_4 conversion aspects are not currently included in the forest product sector module.

Initial Conditions of Forest Product Pools

In order to calculate the C budget for a particular year, it is necessary to specify the initial conditions for each of the C pools of forest products. The quantity and age-class distribution of wood products in landfills, and the quantity of wood in houses and other uses, must therefore be determined.

One way of obtaining such data would be to carry out a study of housing and landfills in order to estimate their inventories of remaining quantities of wood products. This approach is impractical for two main reasons: first, because this C budget applies to all forest products produced from Canadian forests, it would necessitate a worldwide survey to determine what fraction of wood products used in each country is derived from Canada; and second, the necessary information on individual landfills would be very difficult to obtain.

Current C pools are simulated, instead, by starting this part of the module at a point many years in the past and running it forward, using historical harvest rates to generate the C content for each of the four C pools. In the Phase I model, the C pools were initiated by starting the module 40 years prior to 1986 (i.e., 1947) and simulating the C dynamics up to the reference year 1986. To make this approach work, it was necessary to introduce changes in the production parameters to reflect historical conditions. Two main parameters were adjusted over the 40-year simulation (Appendix 6):

1. the conversion efficiency of softwood sawlogs into lumber was gradually increased from about 35% to 45% over the 40-year period; and
2. the use of sawmill chips for pulping was increased from zero for the years before 1972 to about 80% of 1986 levels by 1982.

Additional Assumptions

The forest product sector module represents a fairly simple accounting structure that tracks the transfer of C. A number of assumptions have been made, both in the module structure and in the data that have been used to estimate model parameters. To some extent, all of the parameters used in the module (see Appendix 6) are assumptions, but the following appear to be the most significant:

1. the distribution of harvest among ecoclimatic provinces within a province has been historically stable;
2. the same distribution of harvests among ecoclimatic provinces is used for all types of wood (softwood and hardwood saw timber, pulpwood, and fuelwood);
3. inputs to the various forest product pools prior to 1947 did not affect forest product C emissions into the atmosphere in 1986;
4. the historical patterns of retention of products in the various forest product pools and in landfills remained stable during the 40 years before 1986; and
5. the major changes in the forest product sector related to the C budget for the years 1947–1986 were an increase in the conversion efficiency of softwood sawlogs to lumber, and an increase in the proportion of sawmill chips used for pulp.

Calculation of the Carbon Budget

The main C integration module integrates the simulation of ecosystem C dynamics for all spatial units on a national scale. Within each spatial unit are many different strata, which are recognized according to the combinations of classifiers listed in Table 1. The C dynamics of the biomass and soil C pools of those strata (combinations of classifiers) for which biomass values are available (Bonnor 1985) are described in look-up tables generated by the table-building module (Fig. 2). These look-up tables quantify the pool sizes and the annual rate of change of the biomass and soil C pools.

In Phase I of this study the net C budget of the Canadian forest sector is calculated for a time-step of one year (i.e., 1986) (see also page 7).

The main C integration module performs the following five tasks:

1. the module calculates, for each of the eight biomass and three soil C pools, the total ecosystem C in each stratum within each spatial unit by multiplying the area in each stratum by the biomass and soil C densities (t C ha^{-1});

2. the module calculates, for the eight biomass and three soil C pools, the total changes in ecosystem C associated with biomass and soil C dynamics by multiplying the area in each stratum by the annual rate of net change of biomass and soil C pools (t C ha^{-1});

3. the module calculates net C transfers associated with the five disturbance types as they occur in each spatial unit (as discussed on page 18);

4. the module calculates the quantity of biomass C passed to the forest product sector module; and

5. the module reports results in an output format suitable for the report-generating module.

The integration module incorporates several assumptions that reflect current understanding of ecosystem C dynamics. As discussed on page 11, the biomass C curves represent net C changes. It is assumed that all increases in the sum of the eight biomass C pools have been withdrawn from the atmosphere in the form of CO_2, because photosynthesis is the only pathway by which C can initially be sequestered. On the other hand, in the absence of disturbances, all decreases in total biomass C are assumed to have been caused by the transfer of C to either the fast or medium soil C pool. The receiving soil C pool depends on the biomass pools that are providing the detritus (e.g., foliage biomass is added to the fast soil C pool, while stem biomass is added to the medium soil C pool).

Decreases in the total C contained in the three soil C pools are regarded as atmospheric releases, whereas increases in the total pool size are treated as uptake from the atmosphere, albeit through the biomass C pools. Therefore, a forest ecosystem can remove C from the atmosphere, even when the total biomass C pool is constant (or even declining), if the soil C pools are increasing rapidly enough.

In addition to the annual detrital transfer of C associated with litter fall and tree mortality, event-specific C transfer occurs during disturbances (see page 18). It is important to recall that dead standing trees (e.g., after a fire) are considered part of the soil C pools, which include coarse woody debris and litter. Disturbances therefore not only release C to the atmosphere but also transfer C to the soil C pools.

Postdisturbance biomass dynamics are assumed to be independent of the disturbance type, but soil C dynamics differ between stands regenerating from different disturbances (Fig. 11). Bonnor (1985) contains no information about the disturbance that precedes stand establishment. Assumptions must therefore be made about the disturbances prior to stand establishment in order to determine the initial states of soil C pools (see page 30). On an area basis, wildfire is historically the primary disturbance type in Canada, and the assumption was therefore made that all stands in the inventory originated from fire. The implications of this assumption for the soil C dynamics in the budget are discussed on page 48.

The eventual release into the atmosphere of C accumulated through the annual transfer of biomass C to the forest product sector is accounted for in the forest product sector module. In a given year (1986 in this analysis), the atmospheric C release includes the decomposition of residual forest biomass harvested during the preceding years. In addition, C is released during the processing and burning of residues (as waste or for energy generation) associated with the current year's harvest.

RESULTS AND DISCUSSION

The results of six simulation runs of the C budget model are presented in this Phase I report. Only the first run (referred to as the standard run) is discussed in detail. The additional runs were used to explore some of the uncertainties associated with the current available data and assumptions. A description of the standard run and the five runs for sensitivity analysis follows.

Standard run: The results of a single-year simulation were based on the data for reference year 1986.

Sensitivity analysis: Each of these model runs involved changes to only one main model parameter or process:

1. **High biomass run:** To investigate the effects of uncertainties in the biomass data, all biomass data in the inventory were increased by 10%.
2. **High root-to-shoot ratio run:** To investigate the effects of changed assumptions about fine-root inputs to the soil C pools, the simulated input of fine roots into the fast soil C pool was increased by 10%.
3. **High fire run:** To investigate the effects of altered disturbance regimes, specifically wildfires, the area burned annually was increased by a factor of 3 over that used in the standard run.
4. **Stand origins run:** To explore the effects of the assumption that all stands in Canada are of fire origin, the alternative assumption was made that all stands originated after clear-cut logging.
5. **Slow soil run:** To analyze the effects of changes to the partitioning of C leaving the fast and medium soil C pools, the proportion of C entering the slow soil C pool was decreased from 17% to 5% of the C leaving the fast and medium pools.

The results of the standard run are presented as national totals and by ecoclimatic province. The C inventories are reported for biomass, soil, peatlands, and forest product C pools, followed by a discussion of the changes in these pools during the reference year 1986 and the inferred net exchange with the atmosphere. The results of the sensitivity analysis are summarized as national totals only, and are then discussed individually after a detailed presentation of the standard run.

Carbon Pools

Biomass and Soil Carbon Density

Carbon density ($t\ C\ ha^{-1}$) in Canadian forest ecosystems was found to differ greatly between ecoclimatic provinces (Fig. 15), reflecting the differences in growing conditions. The national average biomass C density is 29.6 $t\ C\ ha^{-1}$, and ranges from 5.9 $t\ C\ ha^{-1}$ for the Subarctic Cordilleran ecoclimatic province to 140.6 $t\ C\ ha^{-1}$ for the Pacific Cordilleran ecoclimatic province. Using completely independent empirical data, Botkin and Simpson (1990) estimated the C density of North American boreal forests (including Alaska) to be 19 ± 4 $t\ C\ ha^{-1}$, which is in close agreement with Phase I estimates for the Canadian western boreal forest (19.5 $t\ C\ ha^{-1}$), but somewhat lower than Phase I estimates for the eastern boreal forest (26.9 $t\ C\ ha^{-1}$).

Soil C density in Canadian forest ecosystems also varies greatly between ecoclimatic provinces. The national average is 189 $t\ ha^{-1}$ (Fig. 15). The highest soil C density is found in the Subarctic (346 $t\ ha^{-1}$) and the Subarctic Cordilleran (344 $t\ ha^{-1}$) ecoclimatic provinces, presumably reflecting the slow decomposition rates in those cooler regions. It is important to note that there are very few data on soil C content for some ecoclimatic provinces (Table 6); however, a national review of available data on soil C content of Canadian forest ecosystems has been initiated (M. Apps, unpublished data, 1991).

Total Biomass, Soil, Forest Products, and Peatland Carbon Inventory

The model simulation provides an estimate of the total biomass, soils, and peatland C pools in Canadian

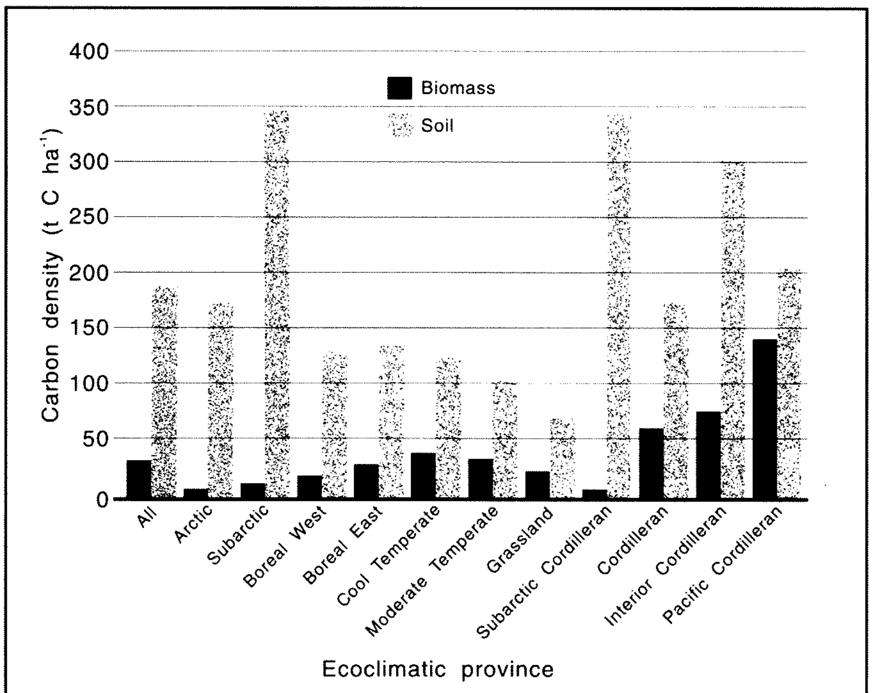


Figure 15. Carbon density of biomass and soil carbon pools for each of the eleven ecoclimatic provinces and the Canadian average.

forest ecosystems, and of the C contained in forest products. Total biomass C for all the areas of the inventory with biomass values attached is 12 Gt C (gigatonne = 10^9 t = 10^{15} g) (Fig. 16; Table 9). Forest soils contain an estimated 76.4 Gt C. This soil estimate does not include C contained in peatlands, which have been independently estimated to contain 135 Gt C (Gorham 1988). Forest products generated from Canadian biomass harvested between 1947 and 1986 are estimated to retain an additional 0.6 Gt C. Each of these components of the total inventory is discussed in more detail below.

To obtain estimates of the total C content of the biomass and soil C pools, the estimates of C density must be multiplied by the appropriate area statistic. The forest areas in the inventory are dominated by four ecoclimatic provinces (Boreal East and West, Subarctic, and Cordilleran), representing 82.3% of the total land area (Fig. 4). The two Boreal ecoclimatic provinces alone account for 43% of the total land area. The unequal distribution of area between the 11 ecoclimatic provinces and the differences in C density both contribute to the observed differences in total biomass and soil C inventory.

The biomass C value of 12 Gt is known to be an underestimation of the total biomass C of Canadian forest ecosystems because biomass values are attached to only 70% of the areas in the CFRDS inventory. These areas do not, however, represent a random sampling of the total forest area. The remaining 30% of the inventory is dominated by unproductive and nonforest land (Table 3). In Phase I, it was not possible to provide an estimate of the biomass contained in the areas for which no data are available, but such an estimate would certainly be less than one obtained by simply extrapolating the estimate of 12 Gt to 100% of the areas in the inventory.

Using essentially the same initial data set but different computational approaches, Bonnor (1985) estimated that Canadian forests contain 26 Gt of oven-dry forest biomass. This amounts to 13 Gt C (assuming a C content of 0.5), an estimate that is 8% higher than the value obtained in this report. The difference can be attributed to three factors:

1. the version of the 1984 biomass inventory data base used for this study was edited (by CFRDS staff) to correct minor technical inconsistencies after the publication of Bonnor's (1985) results;

2. for this report, an age range was assigned to each of the maturity classes of the 1984 biomass inventory, using age-class versus maturity-class relationships derived from Forestry Canada (1988) (see page 13); and

3. instead of using a single average biomass value for each maturity class of the 380 different forest ecosystem types represented in Bonnor (1985), biomass-over-age curves were simulated for those ecosystems.

Each of the above differences in data and methods may contribute to the observed 8% discrepancy between the two estimates. The relative contribution of each of those factors cannot be quantified, however, because it is not feasible to identify the extent of the changes made to the 1984 data base when it was edited.

Biomass C estimates are reported for aboveground biomass only. Adding coarse- and fine-root biomass estimates would further increase the total biomass C content, but insufficient data were available to provide satisfactory estimates of the C contained in roots in Canadian forest ecosystems. Studies of individual ecosystems suggest that an additional 10–20% of the total aboveground biomass is contained in root systems (Dice 1970; Kurz 1989a), and future developments of the model will incorporate dynamics of coarse- and fine-root biomass.

The total soil C estimate is probably an underestimate as well, because soil C dynamics are calculated only for the 70% of the areas in the CFDRS inventory with biomass values. A disproportionately large share of the 30% of the areas without biomass data is located in the Subarctic and Subarctic Cordilleran ecoclimatic provinces, which have high soil C densities. The total soil C estimate for Canadian forest ecosystems may therefore exceed the value obtained by simply extrapolating the estimate in this report to 100% of the areas in the inventory.

Peatlands are represented somewhat simplistically in this model (see page 10). Gorham (1988) estimated the C content of Canadian peatlands to be 135 Gt C, the value used throughout this report. Recently published estimates (Gorham 1991) indicate a C content of between 151.6 Gt (for Gorham's estimated area of 119 million ha) and 119.1 Gt (for the estimated area of 93.5 million ha used by the National Wetland Working Group [1986]). It must be emphasized again that some unknown spatial overlap exists between the inventories of peatlands and forests, and that the estimates of the C content of the peat and soil C pools may not be directly additive. The peatland C pool has been included in the overall C inventory of the forest sector because many peatlands in Canada are forested. Furthermore, it is important to indicate the

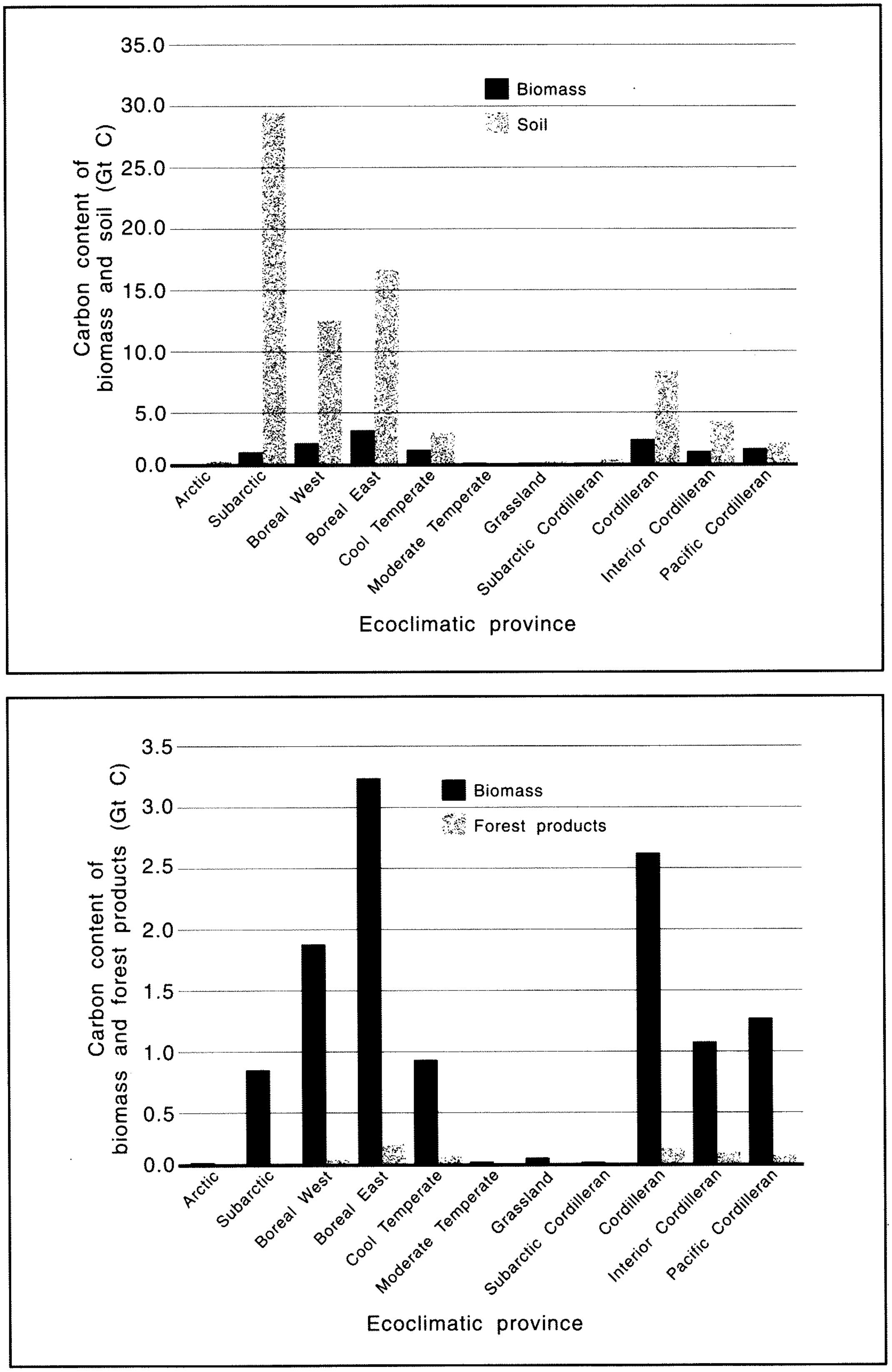


Figure 16. Total carbon content of biomass and soil (upper graph) and of biomass and forest products (lower graph).

Table 9. Carbon inventory of the Canadian forest sector (Mt C)

Variable	Ecoclimatic province											Total
	Arctic	Subarctic	Boreal West	Boreal East	Cool Temperate	Moderate Temperate	Grassland	Subarctic Cordilleran	Cordilleran	Interior Cordilleran	Pacific Cordilleran	
Biomass C	4	817	1 899	3 232	946	7	54	5	2 604	1 099	1 286	11 952
Soil C	114	29 493	12 543	16 418	2 966	20	174	309	8 129	4 383	1 853	76 404
Subtotal	118	30 310	14 442	19 650	3 912	27	228	314	10 733	5 481	3 139	88 356
Forest products sector C	0	0	26	207	64	0	0	0	129	87	51	563
Total	118	30 310	14 468	19 857	3 976	27	228	314	10 862	5 568	3 190	88 918

Note: Totals may not add up due to rounding.

magnitude of the potential C source, should changes in environmental conditions occur due to changes in either management or climate.

The four forest product C pools (see page 33) simulated in the model contain 0.563 Gt C, the equivalent of about 5% of the C contained in forest biomass. This forest product C is distributed through 40 age classes that represent the residues from forest products manufactured during the previous 40 years (Fig. 17). Historic harvest levels, conversion of harvested biomass into forest products, and the C retention curves of these products determine the C retained in each of the age classes. For example, annual inputs to the pulp and paper pool are substantially higher than those to the "other lumber" pool, but the release of C from the pulp and paper pool is much faster. All biomass contained in these forest product pools was harvested from Canadian ecosystems, but its present location may be outside Canada (see page 4).

Carbon Budget of the Canadian Forest Sector

The results of the standard simulation run (Fig. 18; Table 10) show that Canadian forests and forest sector activities in 1986 were a sink of 76.8 Mt C (megatonne = 10^6 t = 10^{12} g), of which 26.2 Mt C were attributed to peatlands. This estimate of net C flux does not account for the C released during the combustion of fossil fuel used in forest management activities or in the manufacturing of forest products.

The two Boreal ecoclimatic provinces accounted for 54% of the net C uptake in the Canadian forest sector, while the Arctic, Subarctic Cordilleran, Grassland, and Moderate Temperate ecoclimatic provinces contributed a total of only 0.94 Mt C (1.2% of the total) to the C sink; however, caution must be exercised when interpreting this result because, for each ecoclimatic province, only those areas included in Bonnor (1985) and those peatland areas included in the national peatland inventory explicitly influence the C budget in this model (Table 3). All ecoclimatic provinces, especially Subarctic and Arctic, contain areas that are treated as "C neutral" in this model. Disturbances are assigned only to areas for which C dynamics are simulated (see page 19).

The net C budget in this report is derived from estimates of net changes in the biomass, soils, peatland, and forest product C pools. In the following pages, each component of this C budget will be discussed in detail.

Forest Biomass

Prior to the accounting for disturbances, the biomass C pools of Canadian forest ecosystems sequestered an estimated 109.3 Mt C, comprising the 92.0 Mt C increase in the biomass C pool and the 17.3 Mt C transferred to the soil C pools as detrital material (litter fall and tree mortality). Carbon uptake is distributed across all forests in Canada.

Every year a small proportion of the Canadian forests is disturbed by fires, insects, or harvesting (Appendix 7). In the reference year 1986, disturbances released 20.3 Mt of the C sequestered in forest biomass directly to the atmosphere. Disturbances also transferred biomass C to the forest product sector (44.2 Mt C harvested biomass) and to the soils pools (55.4 Mt C). The latter transfer consisted of slash and dead standing trees after harvesting, fires, and insect-induced tree mortality (included in the soil C pools in this model).

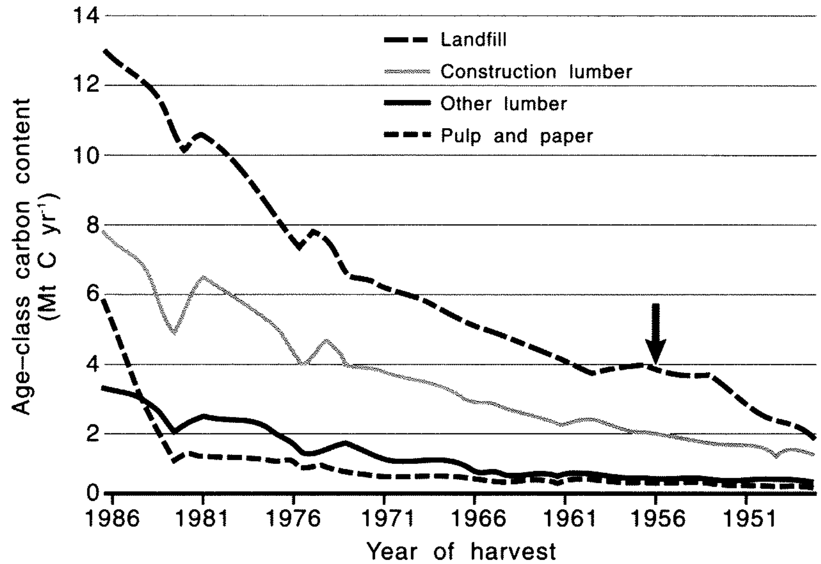
The 10-year-average (1980–1989) area burned annually in Canada is just under 2.5 million ha (Appendix 7). The model results (Table 10) indicate that, in 1986, wildfires released 18.7 Mt of biomass C directly into the atmosphere. In addition, fires transferred 21.0 Mt C from the biomass C pool to the soil C pools—from which C will be released through future decomposition. In areas affected by disturbances, some of the biomass C remains in the biomass pools (see page 19). Slash burning in Canada released 1.5 Mt C into the atmosphere. Almost 60% of the biomass C released into the atmosphere through fires originated in the Western Boreal ecoclimatic province, reflecting the large areas burned there.

As a consequence of defoliation, an estimated 0.1 Mt C was directly released by insect respiration in 1986 (Table 10). The primary significance of insect infestations causing stand mortality, however, is in the transfer of 12.4 Mt C from living biomass to the decomposing soil C pools.

The net change in the biomass C pools in the reference year 1986 was –27.9 Mt C. Harvesting activities transferred 44.2 Mt of biomass C to the forest product sector. The biomass C that remained on the harvested sites (as slash, cull, etc., included in soil C pools) accounted for 22.0 Mt C in 1986. In addition, some living biomass remained on harvested areas and is included in the biomass C inventory.

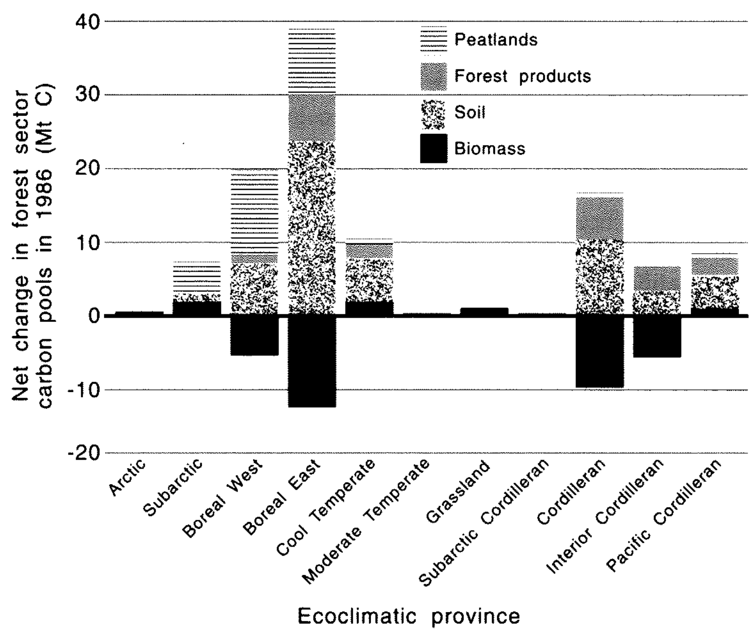
Forest Soils

Prior to the accounting for disturbances, the soil C pools of Canadian forest ecosystems (not including



The pool sizes reflect differences in historical harvesting levels and in product-dependent C retention curves. For example, C in forest products deposited in landfills in 1956 contributed 4 Mt C to the total forest product C pool in landfills in 1986.

Figure 17. Amount of carbon in four forest product pools in each of forty age classes.



Positive values represent net C uptake; negative values represent net C release.

Figure 18. Net change per year in each of the four forest sector carbon pools for the reference year 1986.

Table 10. Carbon budget of the Canadian forest sector for 1986 ('000 t C)

Variable	Ecoclimatic province											Total
	Arctic	Subarctic	Boreal West	Boreal East	Cool Temperate	Moderate Temperate	Grassland	Subarctic Cordilleran	Cordilleran	Interior Cordilleran	Pacific Cordilleran	
Forest biomass												
Net growth before disturbance	30	6 558	19 839	29 436	10 370	188	394	55	12 695	5 699	6 762	92 025
Disturbance releases to atmosphere												
Wildfire	0	−2 523	−11 014	−2 178	−25	0	−9	−8	−2 773	−56	−96	−18 682
Insect	0	0	0	−85	−6	0	0	0	−8	−7	0	−105
Clear-cut and slash burn	0	0	0	−61	−4	0	0	0	−700	−426	−320	−1 511
Subtotal disturbance releases	0	−2 523	−11 014	−2 323	−34	0	−9	−8	−3 482	−489	−416	−20 297
Disturbance transfer to soil												
Wildfire	0	−2 620	−10 749	−3 811	−107	0	−135	−2	−3 084	−316	−129	−20 953
Insects	0	0	0	−9 011	−1 472	0	0	0	−997	−963	0	−12 444
Clear-cut and slash burn	0	0	0	−48	−4	0	0	0	−530	−355	−228	−1 165
Clear-cut	0	0	−1 007	−9 280	−2 385	0	−1	0	−3 700	−2 081	−1 432	−19 887
Partial cut	0	0	0	−389	−62	0	0	0	−115	−314	−31	−910
Subtotal disturbance transfer	0	−2 620	−11 756	−22 539	−4 029	0	−136	−2	−8 426	−4 030	−1 821	−55 359
Transfer to forest products	0	0	−2 605	−16 289	−4 655	0	−1	0	−10 211	−6 588	−3 875	−44 225
Net change	30	1 415	−5 536	−11 715	1 652	188	248	45	−9 424	−5 408	650	−27 856
Forest soils												
Net detrital inputs before disturbance	17	881	3 295	2 533	2 480	−23	49	32	5 002	−445	3 446	17 268
Disturbance transfer from biomass	0	2 620	11 756	22 539	4 029	0	136	2	8 426	4 030	1 821	55 359
Disturbance releases to atmosphere												
Wildfire	0	−2 443	−7 667	−1 472	−29	0	−6	−17	−2 609	−54	−44	−14 342
Insects	0	0	0	0	0	0	0	0	0	0	0	0
Clear-cut and slash burn	0	0	0	−62	−8	0	0	0	−431	−217	−165	−883
Subtotal disturbance releases	0	−2 443	−7 667	−1 534	−37	0	−6	−17	−3 040	−271	−209	−15 225
Net change	17	1 058	7 384	23 538	6 472	−23	179	17	10 388	3 314	5 058	57 402
Forest products												
Transfer from biomass	0	0	2 605	16 289	4 655	0	1	0	10 211	6 588	3 875	44 225
Releases to atmosphere	0	0	−1 442	−9 467	−2 751	0	−1	0	−4 687	−2 996	−1 762	−23 106
Net change	0	0	1 163	6 822	1 904	0	0	0	5 524	3 592	2 113	21 119
Peatlands												
Net accumulation	208	5 041	11 178	8 424	394	6	0	21	511	0	400	26 184
Total (net sink)	254	7 514	14 189	27 070	10 422	172	427	83	6 999	1 498	8 221	76 848

Note: Positive numbers represent increases in C pools, negative numbers represent C release to the atmosphere or transfers to other C pools. Both refer to changes during the reference year 1986. Totals may not add up due to rounding.

peatlands) increased by an estimated 17.3 Mt C in 1986. This net increase is the simulated balance of detrital inputs (including tree mortality and fine-root turnover) of C from the biomass C pools and decomposition losses to the atmosphere from all Canadian forest ecosystems. As with the estimates of soil C density, it must be emphasized that there is a scarcity of data from which to estimate soil C dynamics and against which to compare the estimates of soil C dynamics.

A small proportion (0.86%) of Canadian forest ecosystems was affected by disturbances in 1986. Disturbances released an estimated 15.2 Mt C directly into the atmosphere. Fires accounted for 14.3 Mt C of that release, and slash burning released an additional 0.9 Mt C from the soil C pools directly into the atmosphere. Disturbances transferred 55.4 Mt of biomass C to the soil C pools.

The net change in the soil C pools in the reference year 1986 was 57.4 Mt C. The C pools in Canadian forest ecosystems (not including peatlands) thus increased by 29.5 Mt C, the sum of the biomass and soil C pool changes.

Forest Products

Once removed from the ecosystem, biomass C is considered part of the forest product sector. The forest product C pool dynamics are assigned to the spatial unit in which the harvested material originated. C is released from harvested materials during all stages of processing, product use, and final disposal. The net flux of C from the forest product sector is the difference between C added annually from logging activities and the release of C from processing, burning, and decomposition of forest products.

Two independent estimates of data for 1986 harvest levels are possible. The amount of C received by the forest product sector can be estimated from forest product statistics (see page 35). By applying the annual statistics of areas harvested to the biomass inventory of the C budget, a second estimate can be obtained from the biomass C removed from the ecosystems and transferred to the forest product sector. It was anticipated that there would be a difference between these two estimates because the biomass statistics reflect average stand conditions, while harvesting activities often focus on stands of higher-than-average volumes.

For this study, rules were developed by which areas harvested are assigned to forest types in each of the 41 spatial units represented in the C budget inventory. For each spatial unit, the minimum stand volume needed before a stand was eligible for logging was identified (cf. page 19). The harvesting disturbances applied to the model resulted in the transfer of 39.5 Mt C to the forest product sector.

Canadian forest product statistics indicate that about 177 million m^3 of wood enter the forest product sector annually. That figure represents 44.2 Mt C (using a volume-to-C conversion factor of 0.25). Although that estimate is about 12% higher than the estimate obtained directly from this model, the estimated transfer of 44.2 Mt C was used in the C budget (Table 10) to be consistent with the processing of the harvesting data from 1947–1986. In future model development the conversion of harvested wood volume to units of C will be reviewed, making use of recently published statistics on the wood densities of Canadian tree species (Gonzalez 1990).

The processing of the 44.2 Mt C biomass input during the reference year of 1986, and the oxidation of forest products originating from biomass harvested during the previous 40 years, released 23.1 Mt C to the atmosphere. Nevertheless, the forest product pools showed a net accumulation of 21.1 Mt C in 1986.

In the Phase I model the estimate of C flux from the forest product sector does not account for any energy usage during processing and manufacturing, nor does it account for any bioenergy substitution for fossil fuels. An assessment of the energy use and energy requirements of the forest sector will be conducted in the future.

Peatlands

Canadian peatlands are often forested and are therefore included in this budget (see page 10). Based on the assumption that peatlands are currently accumulating C at the same rate as in the past (28 g m^{-2} yr^{-1}; see page 10), Canadian peatlands were a net sink of 26.2 Mt C, which represents about 34% of the overall net C uptake in the Canadian forest sector in 1986. Peatland contributions to the C budget model are specified in Appendix 2 of this report.

Carbon Pool Changes on an Area Basis

Annual changes in C pools are the net result of two processes operating at different spatial scales. Continuous biomass and soil C pool dynamics from all Canadian forest ecosystems yield small net changes per hectare over a very large area. Every year, event-specific disturbances affect a small proportion of the forest area, but they have a large impact on C pools in those areas.

The net C increase (i.e., excluding litter fall losses) in forest biomass prior to disturbances was 92 Mt C. This increment of approximately 0.23 t C ha^{-1} yr^{-1} is roughly equivalent to a net volume increment of 1 m^3 ha^{-1} yr^{-1}, with uptake rates differing between ecoclimatic provinces, forest types, and stand developmental stages. After accounting for disturbance releases to the atmosphere and C transfers to the soil and forest product pools, the biomass pools decreased by 0.07 t C ha^{-1} yr^{-1} (Fig. 19). Disturbances are the cause of the reductions in biomass C pool sizes in the Boreal East, Boreal West, Cordilleran, and Interior Cordilleran ecoclimatic provinces.

Soils may be either net sources or net sinks of C, depending on the stage of stand development and the length of time since the last disturbance. On average, Canadian forest soils, excluding peatlands, accumulated about 0.14 t C ha^{-1} yr^{-1}. Peatlands accumulated 0.28 t C ha^{-1} yr^{-1}, but the total area of peatlands is less than one-quarter of the total forest area.

The estimates of C released to the atmosphere from fires represent a national average C release of 7.5 and 5.7 t C ha^{-1} from burned area biomass and soil C pools, respectively. These values differ between ecoclimatic provinces and are consistent with current estimates of C release from wildfires in Canada (B. Lawson, personal communication, May 1990; B. Stocks, personal communication, May 1990).

The net change of C pools on an area basis (excluding uptake in the peatland C pool) averaged 0.125 t ha^{-1} yr^{-1} for all of Canada's forest ecosystems (Fig. 19). The highest per-hectare net increase in C pools (0.855 t ha^{-1} yr^{-1}) was observed in the Pacific Cordilleran ecoclimatic province, the area with the greatest per-hectare biomass values (Fig. 15). The high C accumulation rate for the biomass pool of the Moderate Temperate ecoclimatic province is the result of the complete absence (in the model) of disturbance statistics for this small spatial unit (0.05% of total area in the inventory). For the same reason, the soil C pool is decreasing in the Moderate Temperate ecoclimatic province.

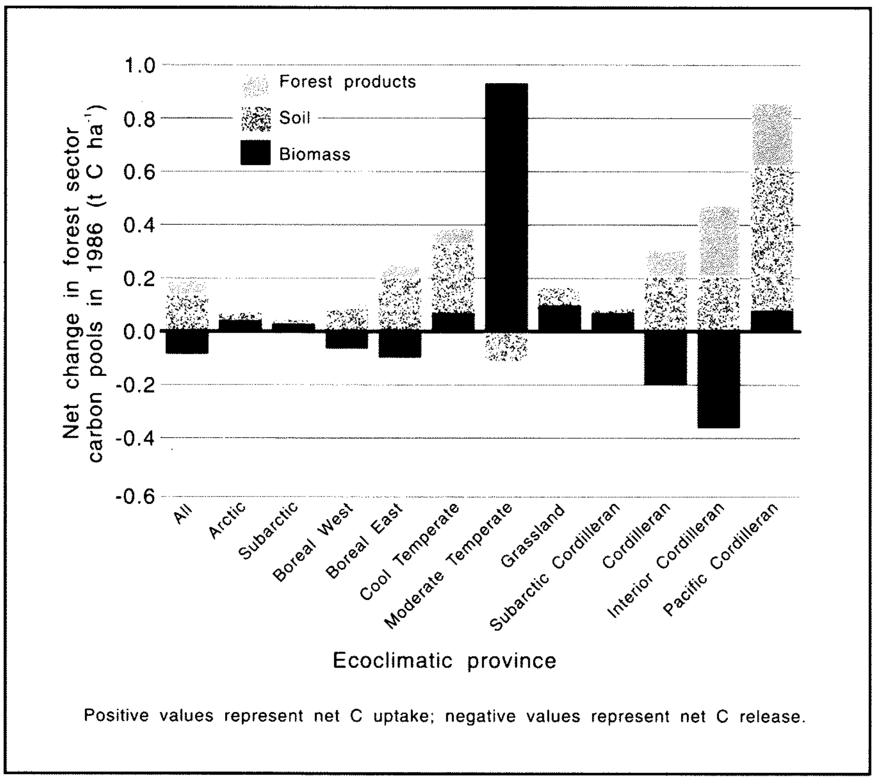


Figure 19. Net change per hectare per year in each of the three forest sector carbon pools (excluding peatlands) for the reference year 1986.

Sensitivity Analysis: Biomass Data

A run of the model was performed to examine the sensitivity of the standard run results to changes in the biomass inventory data. Partial motivation for this analysis is the fact that Bonnor (1985), using an earlier version of essentially the same data set, estimated a total biomass approximately 8% greater than the 12 Gt C obtained from the standard run of this model (see page 37). For this analysis, all biomass data on which the model is based were multiplied by a factor of 1.1, thereby increasing the biomass accumulation curves and all biomass C pools by 10%.

This 10% increase in biomass affected the estimates of both biomass and soil C pool changes (Table 11). As expected, the total biomass C inventory and the uptake of C increased by 10%. The increased biomass resulted in a higher litter fall input to the soil C pools, causing a 10% increase in soil C uptake and a 1% increase in the soil C inventory.

Increased biomass and soil C pool sizes also resulted in greater amounts of C released during disturbances; the

Table 11. Sensitivity analysis results of the carbon budget and inventory for the Canadian forest sector for the standard run of the model and for five additional runs (results are expressed both in units of carbon and percentage change relative to the standard run)

Variable	Sensitivity results (Mt C)						Sensitivity results (%)				
	Standard run	High biomass	High RS[a] ratio	High fire	Stand origin	Slow soil	High biomass	High RS ratio	High fire	Stand origin	Slow soi l
CARBON BUDGET											
Forest biomass											
Growth	92.0	101.2	92.0	92.0	92.0	92.0	10.0	0.0	0.0	0.0	0.0
Disturbance release to atmosphere											
Wildfire	−18.7	−20.5	−18.7	−56.0	−18.7	−18.7	9.9	0.0	199.9	0.0	0.0
Insects	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	9.5	0.0	0.0	0.0	0.0
Clear-cut and slash burn	−1.5	−1.6	−1.5	−1.5	−1.5	−1.5	5.0	0.0	0.0	0.0	0.0
Subtotal disturbance releases	−20.3	−22.2	−20.3	−57.6	−20.3	−20.3	9.6	0.0	184.0	0.0	0.0
Disturbance transfer to soil	−55.4	−61.2	−55.4	−97.3	−55.4	−55.4	10.6	0.0	75.7	0.0	0.0
Transfer to forest products	−44.2	−44.2	−44.2	−44.2	−44.2	−44.2	0.0	0.0	0.0	0.0	0.0
Net change	−27.9	−26.5	−27.9	−107.0	−27.9	−27.9	−5.0	0.0	284.5	0.0	0.0
Forest soils											
Net detrital inputs	17.3	19.0	20.8	17.3	22.3	18.0	10.0	20.7	0.0	29.2	4.4
Disturbance transfer from biomass	55.4	61.2	55.4	97.3	55.4	55.4	10.6	0.0	75.7	0.0	0.0
Disturbance releases											
Wildfire	−14.3	−14.7	−14.4	−43.0	−14.3	−14.4	2.3	0.4	199.8	−0.5	0.4
Insects	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Clear-cut and slash burn	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9	1.4	2.4	0.0	−4.0	0.0
Subtotal disturbance releases	−15.2	−15.6	−15.3	−43.9	−15.1	−15.3	2.2	0.5	188.2	−0.7	0.4
Net change	57.4	64.7	60.9	70.7	62.5	58.1	12.6	6.1	23.1	9.0	1.2
Forests products											
Transfer from biomass	44.2	44.2	44.2	44.2	44.2	44.2	0.0	0.0	0.0	0.0	0.0
Releases to atmosphere	−23.1	−23.1	−23.1	−23.1	−23.1	−23.1	0.0	0.0	0.0	0.0	0.0
Net change	21.1	21.1	21.1	21.1	21.1	21.1	0.0	0.0	0.0	0.0	0.0
Peatlands											
Net accumulation	26.2	26.2	26.2	26.2	26.2	26.2	0.0	0.0	0.0	0.0	0.0
Total (net sink)	76.8	85.5	80.4	10.9	82.0	77.6	11.3	4.6	−85.9	6.7	0.9
CARBON INVENTORY											
Biomass C	11 952	13 147	11 952	11 952	11 952	11 952	10.0	0.0	0.0	0.0	0.0
Soil C	76 404	77 138	76 553	75 860	76 018	76 818	1.0	0.2	−0.7	−0.5	0.5
Subtotal	88 356	90 285	88 505	87 812	87 970	88 770	2.2	0.2	−0.6	−0.4	0.5
Forest products sector	563	563	563	563	563	563	0.0	0.0	0.0	0.0	0.0
Total	88 918	90 848	89 068	88 375	88 533	89 332	2.2	0.2	−0.6	−0.4	0.5

[a] RS ratio = root-to-shoot ratio.

Note: Totals may not add up due to rounding.

disturbance release of C into the atmosphere from biomass increased by 9.6%, whereas from soil C, the disturbance release of C increased by 2.2%. The transfer of biomass C to the soil C pool resulting from disturbances increased by 10.6%.

Results of this run are consistent with what was anticipated, given the model's structure and the relationships between the various C pools and fluxes. This sensitivity analysis indicates that if a systematic bias is present in the biomass data, it will be directly reflected in the simulation of the C pool size and in the simulated releases to the atmosphere. The result is also in agreement with the idea that increases in forest productivity (e.g., through appropriate forest management) also result in increased ecosystem C sequestration.

Sensitivity Analysis: Biomass Carbon Allocation (Root-to-Shoot Ratio)

This run of the model examined the parameterization of fine-root detrital inputs to the soil C pool. Increased production of fine roots is expected to lead to greater root input to the fast soil C pool. If decomposition rates are not altered, the increased root input should result in a small buildup of both the fast and slow soil C pools, with the latter receiving humified materials from the fast C pool (see page 21). The C budget model simulates the rate of biomass C input to the fast and medium C pools as a function of aboveground biomass (see page 27). Fine-root detrition is simulated as a function of foliage biomass. For this model run, the rate of fine-root input to the fast soil C pool was increased by 10%.

An additional reason for interest in the model's sensitivity to fine-root input parameters was the suggestion that changes in climate and atmospheric CO_2 levels will change the allocation of photosynthate between aboveground and belowground biomass. One of the proposed mechanisms is the growth enhancement associated with the CO_2 fertilization effect (Melillo et al. 1990). Increased CO_2 concentrations in growth chamber experiments have usually resulted in enhanced productivity and shifts in the internal C allocation of plants to their root systems. In these experiments, as leaf area becomes the less-limiting plant component, a greater proportion of resources is thought to be allocated to the acquisition of nutrients and water through the roots (Cannell 1985; Kurz 1989b). Therefore, the model has been used to explore the potential quantitative implication of such ecosystem productivity shifts for the C budget of the Canadian forest sector.

The results of this model run yielded no changes in either the biomass pool size or the net growth of the biomass C pool. The total C uptake of ecosystems increased by 3.6 Mt C (Table 11), which was reflected entirely in the 20.7% increase in the soil C pools (prior to accounting for disturbances). This increase resulted from greater fine-root inputs to the soil C pools.

After disturbance releases into the atmosphere and transfers from the biomass C pool were accounted for in the soil C dynamics, the net change in the soil C pool was 6.1% greater than in the standard model run, and the total sink increased by 3.5 Mt C, or 4.6%. The greater C uptake was also reflected in a small (0.2%) increase in the total soil C inventory.

The increase of fine-root input to the fast soil C pool also affected the rate at which humified material from the fast soil C pool was transferred to the slow soil C pool. This in turn affected the rate of C release from the slow soil C pool (see page 49).

This result demonstrates that small changes in internal tree C allocation (in response to environmental changes) can affect the C budget of the Canadian forest sector. These changes in C allocation cannot be detected in forest ecosystems without detailed process-level field studies.

Sensitivity Analysis: Areas Burned Annually

The area burned annually in Canada is highly dependent on the prevailing annual climatic conditions and varies greatly between years; because of this variability, a decision was made to use the 10-year-average (1980–1989) size of area burned annually in the standard model run (as opposed to a specific year's data). The results of the model run presented in this phase explore the implications of using a different estimate of area burned annually. All fire statistics were increased by a factor of 3, thus increasing the area burned annually from 2.5 to 7.5 million ha. The assumed spatial distribution was identical to that of the standard run; the proportion of area burned in each ecoclimatic province was not altered.

It is worth noting that the estimate of area burned annually that was used in this model run is only slightly larger than the area actually burned in 1989 (approximately 7 million ha). The spatial distribution of fires in 1989, however, is unlikely to be identical with that used in this model run.

The simulated impact of the increased fire regime on the net C flux was consistent with the expected behavior of the C budget model. Release of C from biomass and soil increased by 200% (Table 11). Transfer of biomass C to the soil C pool associated with disturbances increased by 75.7%. The net changes in the biomass C pool and the soil C pool were –107.1 Mt C and +70.7 Mt C, respectively.

The overall forest sector C balance in the high-fire scenario represented a C sink of 10.8 Mt C, but only because peatlands contribute a sink of 26.2 Mt C to the budget. During a year of extreme fire conditions—usually caused by prolonged drought—biomass growth may also be reduced and peatland C dynamics affected. This sensitivity analysis only explored the effect of increased fire rates, but it is recognized that other aspects of the C budget are also influenced by the factors that cause the enhanced fire conditions.

It must be emphasized again that the C budget model results reported in this study are from the simulation of a single time-step. The prediction of increased C release associated with the threefold increase in fire rates therefore includes only the consequence of the first-year impacts. Disturbances, including fire, not only transfer C at the time of disturbance but also affect the biomass and soil C dynamics in subsequent years. Burned ecosystems contain large quantities of decomposing organic matter (transferred by the fire to the soil pool), which subsequently release C. The forest growing prior to the fire is replaced by early successional vegetation, which will take up less C initially than the older forest. Areas recently burned may thus continue to be C sources for the atmosphere until the rate of C sequestration through biomass and soil C accumulation is greater than the C releases from decomposition. Therefore, the temporal and spatial integration of ecosystem C dynamics is required to assess properly the long-term impacts of changes in disturbance regimes.

The need for such integration is highlighted by recent fire statistics, which show that the 10-year-average area burned annually in Canada has increased from approximately 1.0 million ha in the period 1950–1970 to 2.5 million ha in 1980–1989 (Van Wagner 1988). There is general agreement among many scientists that the predicted climatic changes in Canada could further increase both the extent and intensity of the fire regimes (Flannigan and Van Wagner 1991). An analysis of the implications of such changes in disturbance regimes is the object of ongoing research.

Sensitivity Analysis: Assumptions about Stand Origin

This run of the model was used to explore the implications of the initial stand conditions. The alternate assumption was made that all stands in the C budget inventory originated from clear-cut logging rather than from fire (as in the standard run).

Every forest stand in Canada is regrowing after some form of disturbance. Even the old-growth stands of Canada's west coast have experienced fires, as suggested by the charcoal buried in thick forest floors. The frequency of past disturbances affects the age-class distribution of Canada's forests and is reflected in the national forest inventories. Disturbances also affect the subsequent dynamics of biomass and soil C pools. Fires, for example, kill much of the living biomass and burn off many of the small-size biomass components, such as foliage, branches, and small stems. Larger stems remain on the site and are added to the soil C pool, from which C is released into the atmosphere through decomposition. Logging, in contrast, removes most of the stem biomass, leaving behind foliage, branches, and tree tops, which are all added to the soil C pools. This disturbance difference is reflected in the size of the fast and medium soil C pools of the two graphs for wildfire and clear-cuts (Fig. 11).

In the Phase I model, biomass C accumulation curves are assumed to be independent of the disturbance type that preceded stand establishment. The assumption of the disturbance origin of stands therefore affected only the initial soil C pool size in the simulation of C dynamics for 1986.

In this Phase I study, it was assumed for the standard run that all forest stands were of fire origin (see page 36). Obviously, other disturbances have contributed to the existing age-class structure of the forests in Canada, but Bonnor (1985) gives no information about the disturbance type that preceded stand establishment. This sensitivity analysis is based on the alternate and drastic assumption that all stands were of clear-cut logging origin. As a result, different soil C dynamics were simulated for each forest stand (see page 30). For this sensitivity analysis, no attempt was made to quantify historical logging practices (such as calculating the percentage of stem biomass removed). The same clear-cut logging disturbance matrix used for the 1986 standard run was also used for the sensitivity analysis. Furthermore, no attempt was made in this sensitivity analysis run to account for the C release from forest product pools, although it is recognized that these pools would be significantly larger if past disturbances resulted from clear-cut logging only.

The results of this sensitivity analysis run indicated that soils become a stronger C sink when integrated for all of Canada, taking up an additional 5.1 Mt C—an increase of 29.2% over the standard run (Table 11). The total C budget, however, increases by only 6.7%.

The change in this assumption of stand origin—from fire to clear-cut logging—essentially altered the timing of the C release from forest ecosystems. Clear-cut logging removes slowly decomposing biomass (large stems) from the forest ecosystem. The reduced soil C decomposition is reflected in the higher net C uptake by the soil C pools. As stated above, this sensitivity analysis ignores the fact that if all stands originated from clear-cut logging, a much greater forest product pool would exist somewhere and its C release from decomposition would offset some or all of the soil C uptake.

Sensitivity Analysis: Changes in Carbon Transfer to the Slow Soil Carbon Pool

The C input to the slow soil C pool originates solely from the fast and medium soil C pools (see page 27). In the standard model run it is assumed that 17% of the C leaving the fast and medium soil C pools is transferred to the slow soil C pool. Because the remainder (83%) is immediately released into the atmosphere, it was decided to explore the sensitivity of the model results to changes in this carbon-partitioning assumption by reducing the 17% entering the slow soil C pool to 5%.

At first glance the effect of changing the partitioning parameter is counterintuitive; the primary effect is to alter the amplitude of changes to the slow soil C pool over the course of a rotation. In contrast with all other decomposition rate parameters (which are externally assigned specific parameter values), the rate at which C leaves the slow soil pool is calculated internally by the model to satisfy an assumed boundary condition (see page 23). Specifically, the loss rate is calculated for each ecosystem type to ensure that there is no net change in the slow soil C pool over the course of a rotation.

In this sensitivity analysis the change in assumption yielded a reduced rate of C input to the slow C soil pool, and the model recalculated a lower rate of C output from this pool to meet the assumption of a dynamic steady-state. The reduction in C loss from the slow C pool affected the pool's C dynamics. The decrease in the size of the slow C pool is reduced in early stand developmental stages (during which C input from the fast and medium C pools is low), thus dampening the amplitude of the dynamics (Fig. 20). This effect is more pronounced in a hardwood forest, where the annual input of foliage litter fall yields higher C turnover.

The results of this sensitivity analysis run showed that the net effect on the C budget was surprisingly small, the total net C uptake increased by 0.7 Mt C, or 0.9% (Table 11). The net soil C uptake increased by 4.4%, and the total C inventory increased by 0.5% over that of the standard run. As expected, there was no effect on the net biomass C dynamics.

During the development of the soils module, the assumption was introduced that the slow soil C pool is in a dynamic steady-state. The results of this sensitivity analysis run emphasize the potential importance of this assumption, which essentially counteracts the effect of the parameter changes made for the sensitivity analysis.

Climate change, forest management activities, and changes in disturbance regimes may result in a deviation from the assumed steady-state condition. There is an immediate need to better quantify the dynamics of the slow soil C pool and to identify the effects of global change on those dynamics. In the next phase of this project, simulation of the dynamics of the slow soil C pool will be represented without dependence on the steady-state assumption.

Discussion

The results of the C budget model indicate that, based on the existing data and the assumptions used in the model, the Canadian forest sector was a net C sink of 76.8 Mt C in the reference year 1986, 26.2 Mt C of which were taken up by peatlands. This estimate does not account for the use of fossil fuel energy required for the management of forest ecosystems and for the processing of forest products, nor does it account for the substitution of bioenergy for fossil energy in the forest product sector.

The annual net uptake of C in Canadian forest ecosystems for the reference year 1986 represents 0.034% of the C already stored in these ecosystems, or 0.057% if peatlands are excluded from calculation of the dynamics and the inventory. It may seem surprising that, despite the releases of C through wildfires, logging, and other disturbances, the forest sector remains a net sink of C. There are believed to be two main reasons for this: the area disturbed annually represents only a small fraction (0.86%) of the total forest area; and the current age-class structure of the forest is skewed toward the earlier stages of stand development (regenerating, immature, and mature) that are active C sinks (Forestry Canada 1988).

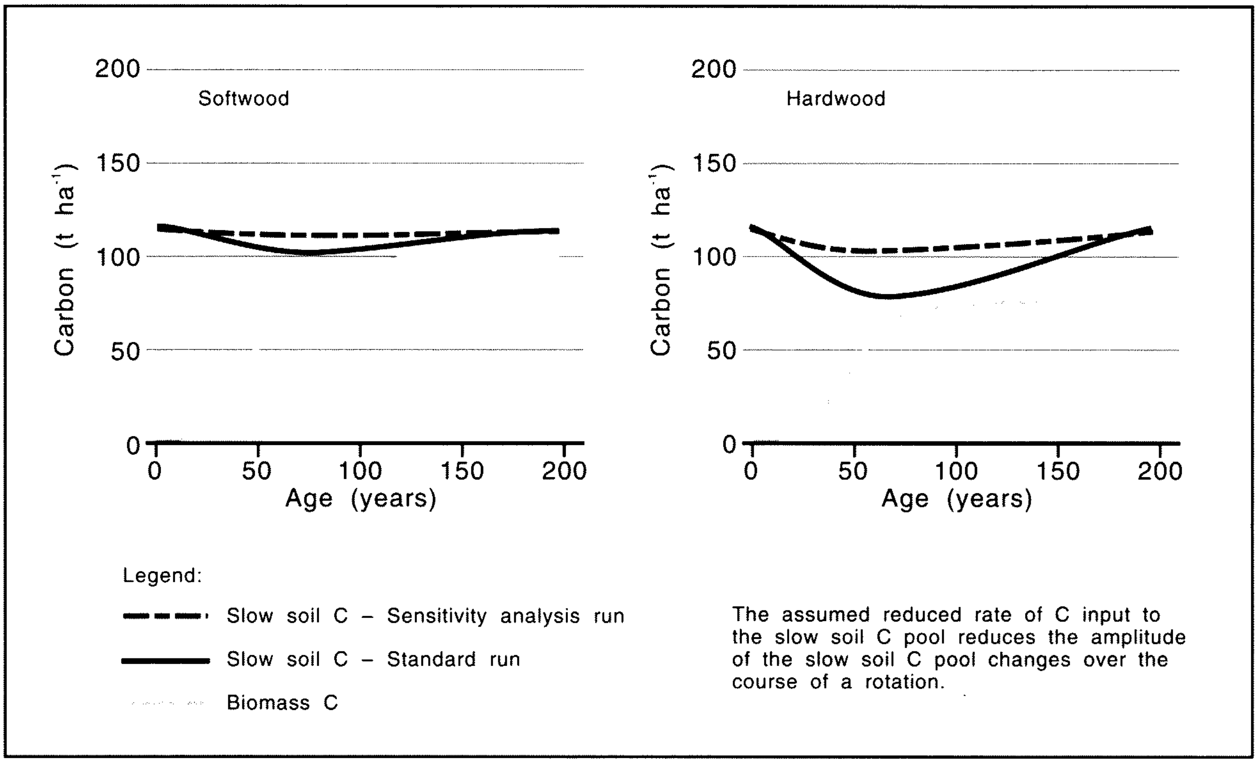


Figure 20. Dynamics of the slow soil carbon pool in the standard run and in the slow soil sensitivity analysis run.

The skewed age-class distribution reflects past disturbances. It implies that the total amount of C currently stored in forest biomass is somewhat lower than the amount that would result from an even distribution of age classes or from one skewed toward older age classes.

The net increase of stored C, which is 0.034–0.057% of the inventory, represents such a small addition of C that it is unlikely this change would be detected in individual ecosystems if it were evenly distributed across all ecosystems and if the measurement period were only 1 year. The rate of change in individual ecosystems is, however, generally much greater with some of them releasing C during and following disturbances, and others accumulating C during stand development. Furthermore, the chronosequence data underlying the growth curves of the model are based on many decades of forest growth, not a 1-year observation period. It is through the spatial and temporal integration of these processes that the net C budget has been calculated.

Many assumptions have been required to compute this C budget. The best available data were used whenever possible, but in many cases expert judgment had to be used. After detailed review of the data and assumptions used in this analysis, future sensitivity analyses should be conducted to explore further the uncertainties associated with the results from this model.

Insects affect the C budget by reducing stand growth (and therefore C accumulation rates) through defoliation, but this phenomenon is not explicitly represented in the model. Endemic levels of insect disturbances, however, are implicitly reflected in Bonnor (1985), which is based on historical stand data showing the effects of endemic insect populations. Climatic changes and pest management programs may affect future insect population dynamics, and their effects on forest growth processes should be considered when assessing climate change and management impacts on the C budget.

The results of the model run that simulated a threefold increase in fire rates demonstrated one possible scenario that would drastically reduce the role of the forest sector as a C sink. It should be noted, however, that the results reported in Phase I assess only a single time-step, and do not account for the role of fire in the long-term dynamics of C sequestration due to stand growth following disturbance.

One of the limitations of simulating a single-year time-step is that it is not possible to state how the results for the reference year 1986 would compare to those for earlier or later years. Even when the year-to-year variations in disturbance levels are disregarded, it is impossible to provide an answer based only on the results from the standard run of the Phase I model. This question will only be answered after new land-use type and biomass accumulation curves have been assigned to all areas affected by disturbances. For example, if all areas affected by disturbances were to stop accumulating forest biomass C (due to permanent regeneration failure, or to conversion to urban or agricultural use), forests would remain as a C sink, although at an ever-decreasing rate, until the release of C exceeded the amount sequestered by the remaining forests. Conversely, enhancing forest productivity, increasing the amount of C retained in forest ecosystems, or increasing the forest area would slowly increase annual C uptake.

The results of the present work emphasize the need to integrate C dynamics carefully over both space and time in order to assess the future impacts of climate change and forest management decisions on the C budget of the Canadian forest sector.

RESEARCH NEEDS

The purpose of this project was to provide a first approximation of the current C budget of Canadian forests and forest sector activities and to develop a tool to calculate such budgets. The strength of this model is derived from its ability to simulate the entire forest sector and to provide answers that put pool sizes and fluxes into perspective. As with every model, some of the model details are oversimplifications of the real system. An analysis of the entire system is needed, however, to determine where research efforts should be directed in order to obtain better data, to review assumptions, or to refine the model structure. A first assessment of the main pools and fluxes in the model highlights those areas where data refinements could most affect the outcome of the C budget.

One of the shortcomings of the Phase I model is the limitation of a single time-step simulation. Although the results of one year provide a "snapshot" of the C budget for 1986, they do not permit the comparison of those results with the C budget for other years or an exploration of the ways in which the C budget is changing as a result of forest sector policy decisions. One of the objectives of the ongoing work on this project is the modification of the C budget model so that it can provide simulations over many decades.

Biomass

The data on biomass C pools in the Canadian forest sector are clearly the data of highest quality in the model. Data are sparse, however, for some forest ecosystem types, such as unproductive or unstocked lands. Adding such data to the inventory will improve the understanding of C dynamics of marginal forest lands. Although the C fluxes may be small on an areal basis, the significance to the C budget may be substantial because of the large areas involved. In the future, remote sensing and other information sources may be used in addition to forest inventories to improve the understanding of vegetation distribution and dynamics.

Currently, biomass accumulation curves are derived from chronosequence data assembled from the biomass inventory, on the assumption that biomass data from stands with similar classifiers (e.g., forest type and site class) but with different maturity classes can be combined to represent a biomass-over-age curve for such stands. The assumption is also that past growing conditions are similar to present growing conditions—this assumption may not be valid for a climate-changed future, and it may be questionable for the reference year 1986. In future phases of this study, the data-driven biomass accumulation curves will need to be replaced by a modeling approach that explicitly takes into account climatic variables and forest management impacts.

The coarse- and fine-root components of forest biomass need to be fully represented in the C budget model. A limited representation of fine-root dynamics is included in this model to account for the contribution of fine-root detritus to soil organic matter dynamics. The proportions of aboveground or stem wood biomass equal to fine- and coarse-root biomass need to be defined for the various forest ecosystem types and stages of stand development.

Postdisturbance accumulation of biomass in forest stands needs to be explored in more detail. The current assumption is that there are no differences in biomass accumulation in stands with similar classifiers but different disturbance histories. Therefore, neither growth improvements through intensive silviculture, tree selection programs, and pest management nor the detrimental effects of site degradation can be accounted for in the present 1-year simulation. There are simply no data with national coverage from which to identify the impacts of specific disturbances on postdisturbance C accumulation rates in biomass. A second problem arises from uncertainties about the amount of living biomass remaining at a site following a disturbance. This problem is of particular concern in forest areas where partial cutting is common practice.

The identification of stand origin (i.e., the disturbance that preceded stand establishment) on a national scale will be a daunting data task. A stand origin statistic is not identified in the national forest inventories, but that information will be required if postdisturbance biomass dynamics are to be specific to disturbance types. Preliminary sensitivity analysis has shown that assumptions regarding stand origin may have some effect on the soil component of the C budget, but more work will be needed to better identify the quantitative implications of different assumptions regarding stand origin.

No assumptions had to be made concerning the length of regeneration delays because in this model only one time-step is simulated. In future work the length of the regeneration delay following disturbances and the rates of C accumulation during the regeneration phase will be identified. The analysis of climate change impacts must be based on a sound understanding of the role of regeneration delays because increased fire frequencies can greatly increase the regeneration delays in boreal and other forest ecosystems; however, effective forest management can significantly shorten or eliminate regeneration delays. Proper representation of those delays is therefore important for the analysis of forest policy options.

National forest inventories incorporate data from a large number of regional and provincial inventories and therefore contain stand information of differing ages. More important, the fate of forest stands since the last survey cannot be identified from the national inventories, and, as the inventory information ages, the proportion of stands with conditions other than those described in the inventory increases. The biomass inventory of Bonnor (1985) is based on Bonnor's (1982) forest inventory and on provincial biomass inventories. There has been no such report on biomass derived from Forestry Canada (1988) and Gray and Nietmann (1989), and there is no known plan to derive a biomass inventory from future forest inventories. Maintaining up-to-date national forest biomass estimates for Canada will be an important contribution to national and international terrestrial C inventories and to studies of global change. The updating of Forestry Canada's national biomass inventory, however, will be a major challenge—well beyond the scope of the C budget modeling project.

Soils and Peatlands

The available data on soil C content and dynamics in Canada are much less complete than the biomass C data. This is particularly true for some of the less-accessible ecoclimatic provinces in Canada, such as the Arctic, the Subarctic, and the Subarctic Cordilleran. Given the pool sizes involved, their contribution to the C budget, and the potential for climate change impacts on soil C fluxes, there is an urgent need to improve the quality of the available data bases on forest soil C contents in Canada. Forestry Canada has already initiated a review process to identify and compile existing data on soil C content in Canadian forest ecosystems.

Postdisturbance soil C dynamics are even less well-documented. Soil C dynamics were simulated for each of the five disturbance types previously described because of the obvious impacts of disturbances on soil C pool sizes and postdisturbance dynamics. The assumptions and data used for these simulations should be carefully reviewed. It is especially important to improve the representation of the dynamics of the slow soil C pool so that the assumption of long-term, dynamic steady-state conditions is replaced by a simulation approach linking the dynamics of the slow soil C pool to climate and stand dynamics. Such an approach is under development in ongoing work.

Peatlands are at present not satisfactorily represented in the C budget model because their geographic locations are not spatially referenced to the forest area information in the biomass inventory. Although many peatlands in Canada are forested, there appear to be no data on the extent of forested peatlands. Their role should be modeled in more detail in the future because of the large quantities of C stored in peatlands as well as the perceived sensitivity of peatlands to changes in climatic conditions. If peatland and forest interactions are to be represented in the model, it will be necessary to identify in the national inventory those forest systems that are growing on peat. The effects of climate change on non-forested peatlands, however, could be simulated in a separate module of the C budget model.

In the current model, soil C pools do not distinguish between the organic matter inputs from hardwood sources and from softwood sources, although decomposition rates are affected by forest type. Whether evidence exists from field experiments to suggest that separate softwood and hardwood soil C pools are required in the model must be investigated.

Disturbances

Disturbances have been found to play a significant role in the C dynamics of Canadian forests, both at the time of disturbance and during postdisturbance stand recovery. (Although the model simulates only a single time-step, all forest stands in the model are assumed to be regrowing following a disturbance that is assumed to have occurred immediately before stand establishment.) The definition of the geographic location of the areas disturbed annually is at present limited to the 41 spatial units represented in the C budget model. Within each spatial unit, disturbances are allocated to stands in the inventory by following a set of rules that identify the stand conditions (e.g., forest type, site class, age, and volume) that make a stand eligible for disturbance. In the future, the extent and geographic location of annual disturbances must be linked to climatic and stand conditions and to forest protection efforts.

Disturbance matrices have been used to define the redistribution of C among the different C pools, the atmosphere, and the forest product sector. The amounts redistributed are defined as proportions of the pool sizes, and this results in varying absolute fluxes because pool sizes differ between ecosystem types and stand developmental stages. The model structure can accommodate one disturbance matrix for each spatial unit and disturbance type ($41 \times 5 = 205$ matrices). At present, the disturbance matrices for wildfires and clear-cut logging with slash burning differ between ecoclimatic provinces to reflect known differences of C releases from fires. For all ecoclimatic provinces, only one matrix is used for each of the remaining three disturbance types. Disturbance matrices should be reviewed carefully because they have a substantial impact on the C budget results. Specifically, there is a need to identify whether regional differences in harvesting practices are accurately represented by current disturbance matrices.

Forest Product Sector

Many of the parameters used in the forest product model are at present based on very limited analyses or on expert judgment. Generating better estimates of all of the parameters used would be a very large task. A more feasible approach would be to conduct sensitivity analyses with the model and to refine those parameters that have the largest effect on model outputs. Several parameter sets can be identified as being less well understood than others:

1. **Landfill dynamics:** Parameters defining the dynamics of the decomposition of landfills on a large scale are only approximated in the forest product model. An intensive literature survey should provide a much better picture of these dynamics, although it may be necessary to carry out field work to obtain some of the required parameter estimates.

2. **Historic parameter values:** The forest product model uses both historical harvest records and values of various historical distribution parameters to generate the sizes of existing forest product and landfill C pools. An examination of the relevant literature could substantially improve the current parameter estimates.

3. **Carbon retention curves:** Each forest product category is assigned to a CRC that defines the proportion of C remaining in that C pool as the forest product ages. Sensitivity analysis should be conducted to explore the response of the C budget to changes in CRC parameters. Policy options, including the production of more durable forest products that retain C for a longer time, can also be explored through changes in CRC parameters.

A more comprehensive representation of the forest product sector will be developed in future work to better account for the many different production processes and forest product categories—in particular, to improve the accounting for both C fluxes and energy use and requirements.

Energy Use

The Phase I version of the C budget model contains a limited simulation of energy use in the forest sector, but the results are not reported in this study because of the paucity of calibration data. Two challenges need to be overcome to better quantify energy use in the forest sector and its implications for the C budget. The energy requirements of the various production processes and of forest management must be identified. It must also be determined whether energy sources release C into the atmosphere and whether the released C originates from fossil sources or from the combustion of biomass.

Biofuels may be used to substitute for fossil energy sources in the forest sector. This appears to be one of the most effective ways of reducing the input of fossil C into the global atmosphere, provided that the regrowth of harvested stands ensures a sustainable wood supply. The implications of energy-use decisions on the C budget will be analyzed in the next phase of this work.

Validation and Verification

Validation and verification of a model are extremely difficult when it operates on the spatial and temporal scales of the Phase I C-budget model. There are, however, feasible approaches that should be pursued.

An example of one validation approach is the application of the same model structure—on a smaller spatial scale—to a well-studied system, such as an ecosystem or a forest region, and the comparison of the model outputs with the data available on C dynamics for that system. The C budget model is currently being revised to operate on a more flexible spatial scale. The C budget model is being linked to a geographic information system (GIS) to allow the integration of information from different spatial data sets.

Impacts of Climate Change

Climate change will affect the C budget at many different levels. Biomass C accumulation will be affected by changes in climatic conditions, as will soil C dynamics and disturbance regimes. There are several potential positive and negative feedback loops in the system. For example, increases in temperature may lead to greater disturbances by fire, which will affect the amount of CO_2 released into the atmosphere, providing positive feedback for further climate changes. Negative feedback may exist between temperature, CO_2 concentration, and tree growth rates. The challenge will be to integrate these various processes properly on the appropriate temporal and spatial scales. There appears to be no alternative to the use of an integrated modeling framework, such as the one described in this report, for conducting the analysis of future C budgets on a national scale.

Forest Policy Decisions

The implementation of different forest policy options can affect the C budget of the Canadian forest sector in various ways. Afforestation and reforestation alter the areas that sequester C or the rate at which C is sequestered in those areas. Changing the protection efforts against fire or insect pests will alter the C release from disturbances, but it will also affect the age-class structure of the forests. Policy decisions in the forest product sector can reduce the rate of fossil C release to the atmosphere by satisfying energy demands through bioenergy. Increasing the timespan that C is retained in forest product can increase the forest product C pool, thus reducing C emissions into the atmosphere. The model structure is being revised to allow quantitative analyses of the combined impacts of such forest policy decisions on the C budget of Canadian forests and forest sector activities.

ACKNOWLEDGMENTS

The authors wish to thank the 26 experts (listed in Appendix 1) from Forestry Canada, several universities, and the forest industry who generously contributed ideas and data at a 3-day workshop sponsored by Forestry Canada. The authors are also grateful for the assistance of the following: J.J. Lowe, K. Power, S.L. Gray, and O.Q. Hendrickson (Petawawa National Forestry Institute); S.C. Zoltai and W.J.A. Volney (Northern Forestry Centre); J.A. Trofymow and B.D. Lawson (Pacific Forestry Centre); and B.J. Stocks (Great Lakes Forestry Centre); as well as others who also supplied data for the model. Many representatives of provincial resource management agencies responded to letters and telephone enquiries from the authors. Special thanks are extended to M.G. Deering and D.C.E. Robinson for programming assistance, and T. Lekstrum and C. Trethewey for research assistance. The authors wish to acknowledge particularly the support and encouragement of J.S. Maini, Assistant Deputy Minister, Forestry Canada, whose foresight in environmental matters was crucial to the initiation of this project.

The reviewers of an earlier version of this report provided many useful suggestions: C.S. Binkley, R.A. Birdsey, G.M. Bonnor, L.G. Brace, P.G. Comeau, J. Dobie, J.P. Hall, M.E. Harmon, O.Q. Hendrickson, R.A. Houghton, J.J. Lowe, J.P. Martell, J.C. Mercier, D.F.W. Pollard, J. Richardson, H.I. Simonson, B.J. Stocks, J.A. Trofymow, and M.T. Wellish.

REFERENCES

Agee, J.K.; Huff, M.H. 1987. Fuel succession in a western hemlock/Douglas-fir forest. Can. J. For. Res. 17:697–704.

Anderson, D.W.; Coleman, D.C. 1985. The dynamics of organic matter in grassland soils. J. Soil Water Conserv. 40:211–216.

Bonnor, G.M. 1982. Canada's forest inventory 1981. Dep. Environ., Can. For. Serv., For. Stat. Syst. Branch, Ottawa, Ontario.

Bonnor, G.M. 1985. Inventory of forest biomass in Canada. Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario.

Botkin, D.B.; Simpson, L.G. 1990. Biomass of the North American boreal forest, a step toward accurate global measures. Biogeochem. 9:161–174.

Bray, J.R.; Gorham, E. 1964. Litter production in forests of the world. Adv. Ecol. Res. 2:101–157.

Cannell, M.G.R. 1985. World forest biomass and primary production data. Academic Press, New York, New York.

Dice, S.F. 1970. The biomass and nutrient flux in a second-growth Douglas-fir ecosystem (a study in quantitative ecology). Ph.D. thesis, Univ. Washington, Seattle, Washington.

Ecoregions Working Group. 1989. Ecoclimatic regions of Canada, first approximation. Environ. Can., Conserv. Prot., Can. Wildl. Serv., Sustainable Dev. Branch, Ecoregions Work. Group, Can. Comm. Ecol. Land Classif., Ottawa, Ontario. Ecol. Land Classif. Ser. 23.

Edmonds, R.L. 1984. Long-term decomposition and nutrient dynamics in Pacific silver fir needles in western Washington. Can. J. For. Res. 14:395–400.

Emanuel, W.R.; Killough, G.C.; Post, W.M.; Shugart, H.H. 1984. Modeling terrestrial ecosystems in the global carbon cycle with shifts in carbon storage capacity by land-use change. Ecology 65:970–983.

Flannigan, M.D.; Van Wagner, C.E. 1991. Climate change and wildfire in Canada. Can. J. For. Res. 21:66–72.

Forestry Canada. 1988. Canada's forest inventory 1986. For. Can., Ottawa, Ontario.

Forestry Canada. 1989. Selected forestry statistics Canada 1988. For. Can., Econ. Stat. Dir., Ottawa, Ontario. Inf. Rep. E-X-41.

Gammon, R.H.; Sundquist, E.T.; Fraser, P.J. 1985. History of carbon dioxide in the atmosphere. Pages 25-62 *in* J.R. Trabalka, editor. Atmospheric carbon dioxide and the global carbon cycle. U.S. Dep. Energy, Washington, D.C. DOE/ER-0239.

Gessel, S.P.; Turner, J. 1976. Litter production in western Washington Douglas-fir stands. For. 49:63–72.

Gonzalez, J.S. 1990. Wood density of Canadian tree species. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-315.

Gorham, E. 1988. Canada's peatlands: their importance for the global carbon cycle and possible effects of "greenhouse" climatic warming. Transact. Royal Soc. Can. V, 3:21–23.

Gorham, E. 1991. Northern peatlands role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1(2):182–195.

Gray, S.L.; Nietmann, K. 1989. Canada's forest inventory 1986—technical supplement. For. Can., Petawawa Natl. For. Inst., Chalk River, Ontario. Inf. Rep. PI-X-86.

Grier, C.C. 1988. Foliage loss due to snow, wind, and winter drying damage: its effects on leaf biomass of some western conifer forests. Can. J. For. Res. 18:1097–1102.

Hansen, J.; Fung, I.; Lacis, A.; Rind, D.; Lebedeff, S.; Ruedy, R.; Russell, G. 1988. Global climate changes as forecast by Goddard Institute for Space Studies three dimensional model. J. Geophys. Res. 93:9341–9364.

Harcombe, P.A.; Harmon, M.E.; Greene, S.E. 1990. Changes in biomass and production over 53 years in a coastal *Picea sitchensis – Tsuga heterophylla* forest approaching maturity. Can. J. For. Res. 20:1602–1610.

Harmon, M.E.; Franklin, J.F.; Swanson, F.J.; Sollins, P.; Gregory, S.V.; Lattin, J.D.; Anderson, N.H.; Cline, S.P.; Aumen, N.G.; Sedell, J.R.; Lienkaemper, G.W.; Cromack, K., Jr.; Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15:133–302.

Harmon, M.E.; Baker, G.A.; Spycher, G.; Greene, S.E. 1990. Leaf-litter decomposition in the *Picea/Tsuga* forests of Olympic National Park, Washington, U.S.A. For. Ecol. Manage. 31:55–66.

Holling, C.S., editor. 1979. Adaptive environmental assessment and management. International series on applied systems analysis. 3. IIASA. John Wiley and Sons, New York, New York.

Honer, T.G.; Bickerstaff, A. 1985. Canada's forest area and wood volume balance 1977–1981: an appraisal of change under present levels of management. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia. Inf. Rep. BC-X-272.

Houghton, R.A. 1986. Estimating changes in the carbon content of terrestrial ecosystems from historical data. Pages 175–193 *in* J.R. Trabalka and D.E. Reichle, editors. The changing carbon cycle: a global analysis. Springer Verlag, New York, New York.

Houghton, R.A.; Hobbie, J.E.; Melillo, J.M.; Moore, B.; Peterson, β.J.; Shaver, G.R.; Woodwell, G.M. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecol. Monogr. 53:235–262.

Keeling, C.D.; Bacastow, R.B.; Whorf, T.P. 1982. Measurements of the concentration of carbon dioxide at Mauna Loa observatory, Hawaii. Pages 377–385 *in* W.C. Clark, editor. Carbon dioxide review: 1982. Oxford University Press, New York, New York.

Kling, G.W.; Kipphut, G.W.; Miller, M.C. 1991. Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. Sci. 251:298–301.

Kurz, W.A. 1989a. Net primary production, production allocation, and foliage efficiency in second growth Douglas-fir stands with differing site quality. Ph.D. thesis, Univ. British Columbia, Vancouver, British Columbia.

Kurz, W.A. 1989b. Significance of shifts in carbon allocation patterns for long-term site productivity research. Pages 149–164 *in* W.J. Dyck and C.A. Mees, editors. Research strategies for long-term site productivity. Proc., IEA/BE A3 Workshop, August 1988, Seattle, Washington. For. Res. Inst., New Zealand. IEA/BE A3 Rep. 8. Bull. 152.

McClaugherty, C.A.; Aber, J.D.; Melillo, J.M. 1984. Decomposition dynamics of fine roots in forested ecosystems. Oikos 42:378–386.

Melillo, J.M.; Aber, J.D.; Muratore, J.F. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecol. 63:621–626.

Melillo, J.M.; Callaghan, T.V.; Woodward, F.I.; Salati, E.; Sinha, S.K. 1990. Effects on ecosystems. Pages 284–310 *in* J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, editors. Climate change, the IPCC scientific assessment. Cambridge University Press, Cambridge, United Kingdom.

Moore, T.R. 1989. Plant production, decomposition, and carbon efflux in a subarctic patterned fen. Arctic Alp. Res. 21:156–162.

National Wetlands Working Group. 1986. Canada's wetlands. a) Canada—wetland regions; b) Canada—distribution of wetland. Dep. Energy, Mines, Resour., Ottawa, Ontario, and Environ. Can., Ottawa, Ontario. Map folio.

Piene, H.; Van Cleve, K. 1978. Weight loss of litter and cellulose bags in a thinned white spruce forest in interior Alaska. Can. J. For. Res. 8:42–46.

Rizzo, B.; Wiken, E. 1989. Assessing the sensitivity of Canada's ecosystems to climatic change. Pages 94–111 *in* E.A. Koster and M.M. Boer, compilers. Landscape ecological impacts of climatic change on boreal/(sub)arctic regions, with emphasis on Fennoscandia. LLIC Proj.

Rotty, R.M.; Marland, G. 1986. Fossil fuel combustion: recent amounts, patterns and trends of CO_2. Pages 474–490 *in* J.R. Trabalka and D.E. Reichle, editors. The changing carbon cycle: a global analysis. Springer Verlag, New York, New York.

Schlesinger, M.E.; Mitchell, J.F.B. 1985. Model projections of the equilibrium climate response to increased carbon dioxide. Pages 81–147 *in* M.C. MacCracken and F.M. Luther, editors. Projecting the climatic effects of increasing carbon dioxide. U.S. Dep. Energy, Washington, D.C. DOE/ER-0237.

Turner, J.; Long, J.N. 1975. Accumulation of organic matter in a series of Douglas-fir stands. Can. J. For. Res. 5:681–690.

Van Wagner, C.E. 1988. The historical pattern of annual burned area in Canada. For. Chron. 64(3):182–185.

Vogt, K.A.; Grier, C.C.; Vogt, D.J. 1986. Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. Adv. Ecol. Res. 15:303–377.

Zinke, P.J.; Stangenberger, A.G.; Post, W.M.; Emanuel, W.R.; Olson, J.S. 1986. Worldwide organic soil carbon and nitrogen data. *In* R.E. Millemann and T.A. Boden, compilers. CDIC numeric data collection. U.S. Dep. Energy, Carbon Dioxide Inf. Cent., Environ. Sci. Div., Oak Ridge Natl. Lab., Oak Ridge, Tennessee. ORNL/CDIC-18. NDP-018.

Zoltai, S.C. 1988. Ecoclimatic provinces of Canada and man-induced climatic change. Can. Comm. Ecol. Land Classif. Newsl. 17:12–15.

APPENDIX 1
LIST OF WORKSHOP PARTICIPANTS

Participant	Affiliation
Mike Apps	Forestry Canada, Northern Forestry Centre, Edmonton
John Balatinecz	Faculty of Forestry, University of Toronto, Toronto
Mike Bonnor	Forestry Canada, Pacific Forestry Centre, Victoria
Lorne Brace	Forestry Canada, Northern Forestry Centre, Edmonton
Josef Cihlar	Canada Centre for Remote Sensing, Ottawa
Jock Dobie	Statistics Canada, B.C. Forestry and Forest Industries, Vancouver
Peter Hall	Forestry Canada, Science Directorate, Hull
Mark Harmon	Department of Forest Sciences, Oregon State University, Corvallis
Ole Hendrickson	Forestry Canada, Science Directorate, Hull
Werner Kurz	ESSA Environmental and Social Systems Analysts Ltd., Vancouver
Ken Lertzman	Natural Resources Management Program, Simon Fraser University, Burnaby
Tamara Lekstrum	ESSA Environmental and Social Systems Analysts Ltd., Vancouver
Joe Lowe	Forestry Canada, Petawawa National Forestry Institute, Chalk River
Vishwa Mathur	Forestry Canada, Industry, Trade and Technology Directorate, Hull
Peter McNamee	ESSA Environmental and Social Systems Analysts Ltd., Vancouver
John Nyboer	Natural Resources Management Program, Simon Fraser University, Burnaby
Dennis Parkinson	Department of Biological Sciences, University of Calgary, Calgary
Doug F.W. Pollard	Forestry Canada, Pacific Forestry Centre, Victoria
Jim Richardson	Forestry Canada, Forest Science Directorate, Hull
Brian Stocks	Forestry Canada, Ontario Region, Great Lakes Forestry Centre, Sault Ste. Marie
Iver Simonsen	Pulp and Paper Research, Institute of Canada, Pointe Claire
Tony Trofymow	Forestry Canada, Pacific Forestry Centre, Victoria
Tim Webb	ESSA Environmental and Social Systems Analysts Ltd., Vancouver
Jan Volney	Forestry Canada, Northern Forestry Centre, Edmonton
Steve Zoltai	Forestry Canada, Northern Forestry Centre, Edmonton

APPENDIX 2
AREA OF PEATLANDS, ESTIMATES OF NET CARBON ACCUMULATION, AND METHANE RELEASE

Total area of peatlands

Ecoclimatic province	Total area of peatlands per administrative province ('000 ha)												Total
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories	
Arctic	1	0	0	0	18	0	1	0	0	0	10	711	741
Subarctic	1 474	0	0	0	2 517	3 492	4 077	137	0	0	504	5 803	18 005
Boreal West	0	0	0	0	0	2 558	12 958	6 751	11 418	982	5	7 808	42 480
Boreal East	2 911	94	0	367	6 090	18 069	0	0	0	0	0	0	27 529
Cool Temperate	0	59	3	118	846	381	0	0	0	0	0	0	1 407
Moderate Temperate	0	0	0	0	0	23	0	0	0	0	0	0	23
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	50	25	75
Cordilleran	0	0	0	0	0	0	0	0	962	597	267	0	1 825
Interior Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	1 429	0	0	1 429
Total	4 386	152	3	485	9 470	24 524	17 036	6 888	12 380	3 007	836	14 347	93 513

Note: Totals may not add up due to rounding.

Net carbon accumulation

Ecoclimatic province	Net carbon accumulation per administrative province ('000 t C)												Total
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories	
Arctic	0	0	0	0	5	0	0	0	0	0	3	199	208
Subarctic	413	0	0	0	705	978	1 142	38	0	0	141	1 625	5 041
Boreal West	0	0	0	0	0	0	3 628	1 890	3 197	275	2	2 186	11 178
Boreal East	815	26	0	103	1 705	5 776	0	0	0	0	0	0	8 424
Cool Temperate	0	16	1	33	237	107	0	0	0	0	0	0	394
Moderate Temperate	0	0	0	0	0	6	0	0	0	0	0	0	6
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	14	7	21
Cordilleran	0	0	0	0	0	0	0	0	269	167	75	0	511
Interior Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	400	0	0	400
Total	1 228	43	1	136	2 652	6 867	4 770	1 929	3 466	842	234	4 017	26 184

Note: Totals may not add up due to rounding.

Methane release

Ecoclimatic province	Methane release per administrative province ('000 t C)												Total
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories	
Arctic	0	0	0	0	0	0	0	0	0	0	0	4	4
Subarctic	9	0	0	0	15	21	24	1	0	0	3	35	108
Boreal West	0	0	0	0	0	0	78	41	69	6	0	47	240
Boreal East	17	1	0	2	37	124	0	0	0	0	0	0	181
Cool Temperate	0	0	0	1	5	2	0	0	0	0	0	0	8
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0
Cordilleran	0	0	0	0	0	0	0	0	6	4	2	0	11
Interior Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	9	0	0	9
Total	26	1	0	3	57	147	102	41	74	18	5	86	561

Note: Totals may not add up due to rounding.

APPENDIX 3
RELATIONSHIPS BETWEEN MATURITY CLASSES AND AGE CLASSES USED IN THE CARBON BUDGET MODEL

This appendix contains 12 data sets, one for each administrative province, describing the relationship between maturity classes and age classes used in the C budget model. The relationships are derived from Forestry Canada (1988).

Codes

Forest type	Maturity class
1 = Softwood	1 = Regeneration
2 = Mixedwood	2 = Immature
3 = Hardwood	3 = Mature
4 = Undetermined	4 = Overmature
	5 = Uneven-aged
	6 = Undetermined

Notes and Assumptions

Values of –1 mean that there are no data available for a maturity class, usually because the inventory does not include this class.

Manitoba: Forestry Canada (1986) does not contain any age-class information from which the relationship between maturity class and age class can be derived. The age-class definitions from Alberta are used instead.

Saskatchewan: Although the maturity-class versus age-class table contains the definitions, the biomass inventory contains only the maturity class "undetermined". Hence, the maximum age for that maturity class is the only information used by the model.

Yukon: Only a small part of the area contains maturity-class definitions, and what is present has been reclassified as "undetermined" (see page 14).

Data set: Newfoundland

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	–1	–1	–1.00
1	2	1	40	19.86
1	3	41	80	66.88
1	4	81	200	98.28
1	5	1	200	100.00
1	6	1	200	100.00
2	1	–1	–1	–1.00
2	2	1	40	26.24
2	3	41	80	66.53
2	4	81	200	90.69
2	5	1	200	100.00
2	6	1	200	100.00
3	1	–1	–1	–1.00
3	2	1	40	24.80
3	3	41	80	67.72
3	4	81	200	90.74
3	5	1	200	100.00
3	6	1	200	100.00
4	1	–1	–1	–1.00
4	2	1	40	20.05
4	3	41	80	66.86
4	4	81	200	97.38
4	5	1	200	100.00
4	6	1	200	100.00

Data set: Nova Scotia

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	11.22
1	2	21	60	47.46
1	3	61	100	74.04
1	4	101	120	109.80
1	5	1	120	60.00
1	6	1	120	60.00
2	1	1	20	11.06
2	2	21	60	47.02
2	3	61	100	73.81
2	4	101	120	110.00
2	5	1	120	60.00
2	6	1	120	60.00
3	1	1	20	11.85
3	2	21	60	55.65
3	3	61	100	75.43
3	4	101	120	110.00
3	5	1	120	60.00
3	6	1	120	60.00
4	1	1	20	11.32
4	2	21	60	49.72
4	3	61	100	74.32
4	4	101	120	109.86
4	5	1	120	60.00
4	6	1	120	60.00

Data set: Prince Edward Island

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	–1	–1	–1
1	2	–1	–1	–1
1	3	–1	–1	–1
1	4	–1	–1	–1
1	5	–1	–1	–1
1	6	1	200	100
2	1	–1	–1	–1
2	2	–1	–1	–1
2	3	–1	–1	–1
2	4	–1	–1	–1
2	5	–1	–1	–1
2	6	1	200	100
3	1	–1	–1	–1
3	2	–1	–1	–1
3	3	–1	–1	–1
3	4	–1	–1	–1
3	5	–1	–1	–1
3	6	1	200	100
4	1	–1	–1	–1
4	2	–1	–1	–1
4	3	–1	–1	–1
4	4	–1	–1	–1
4	5	–1	–1	–1
4	6	1	200	100

Data set: New Brunswick

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	10.00
1	2	21	60	48.58
1	3	61	100	83.76
1	4	101	200	109.97
1	5	1	200	100.00
1	6	1	200	100.00
2	1	1	20	10.00
2	2	21	60	48.40
2	3	61	100	89.35
2	4	101	200	124.35
2	5	1	200	100.00
2	6	1	200	100.00
3	1	1	20	10.00
3	2	21	60	47.01
3	3	61	100	96.94
3	4	101	200	154.85
3	5	1	200	100.00
3	6	1	200	100.00
4	1	1	20	10.00
4	2	21	80	47.94
4	3	81	120	88.24
4	4	121	200	127.38
4	5	1	200	100.00
4	6	1	200	100.00

Data set: Quebec

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	10.00
1	2	21	60	49.49
1	3	61	120	98.97
1	4	121	140	130.00
1	5	1	140	70.00
1	6	1	140	70.00
2	1	1	20	10.00
2	2	21	60	48.22
2	3	61	90	81.59
2	4	91	120	92.47
2	5	1	120	60.00
2	6	1	120	60.00
3	1	1	20	10.00
3	2	21	60	55.92
3	3	61	100	83.77
3	4	101	120	95.90
3	5	1	120	60.00
3	6	1	120	60.00
4	1	1	20	10.00
4	2	21	60	51.51
4	3	61	100	88.08
4	4	101	120	95.04
4	5	1	120	60.00
4	6	1	120	60.00

Data set: Ontario

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	12.20
1	2	21	60	48.77
1	3	61	120	92.09
1	4	121	200	127.61
1	5	1	200	100.00
1	6	1	200	100.00
2	1	1	20	11.01
2	2	21	60	43.16
2	3	61	90	71.99
2	4	91	200	94.44
2	5	1	200	100.00
2	6	1	200	100.00
3	1	1	20	8.48
3	2	21	60	42.54
3	3	61	90	65.77
3	4	91	200	97.38
3	5	1	200	100.00
3	6	1	200	100.00
4	1	1	20	11.60
4	2	21	60	45.88
4	3	61	100	82.78
4	4	101	200	107.37
4	5	1	200	100.00
4	6	1	200	100.00

Data set: Manitoba

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	0	22.24
1	2	41	80	58.76
1	3	81	140	98.86
1	4	141	200	144.56
1	5	1	200	100.00
1	6	1	200	100.00
2	1	1	40	22.86
2	2	41	80	56.66
2	3	81	120	101.24
2	4	121	200	135.61
2	5	1	200	100.00
2	6	1	200	100.00
3	1	1	20	10.00
3	2	21	60	49.47
3	3	61	100	79.91
3	4	101	200	118.98
3	5	1	200	100.00
3	6	1	200	100.00
4	1	1	40	19.68
4	2	41	80	54.55
4	3	81	120	92.96
4	4	121	200	135.78
4	5	1	200	100.00
4	6	1	200	100.00

Data set: Saskatchewan

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	-1	-1	-1.00
1	2	1	60	49.19
1	3	61	100	84.39
1	4	101	200	109.15
1	5	1	200	100.00
1	6	1	200	100.00
2	1	-1	-1	-1.00
2	2	1	60	39.92
2	3	61	80	70.00
2	4	81	200	99.44
2	5	1	200	100.00
2	6	1	200	100.00
3	1	-1	-1	-1.00
3	2	1	60	36.23
3	3	61	80	70.00
3	4	81	200	85.46
3	5	1	200	100.00
3	6	1	200	100.00
4	1	-1	-1	-1.00
4	2	1	60	43.63
4	3	61	90	77.26
4	4	91	200	98.05
4	5	1	200	100.00
4	6	1	200	100.00

Data set: Alberta

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	40	22.24
1	2	41	80	58.76
1	3	81	140	98.86
1	4	141	200	144.56
1	5	1	200	100.00
1	6	1	200	100.00
2	1	1	40	22.86
2	2	41	80	56.66
2	3	81	120	101.24
2	4	121	200	135.61
2	5	1	200	100.00
2	6	1	200	100.00
3	1	1	20	10.00
3	2	21	60	49.47
3	3	61	100	79.91
3	4	101	200	118.98
3	5	1	200	100.00
3	6	1	200	100.00
4	1	1	40	19.68
4	2	41	80	54.55
4	3	81	120	92.96
4	4	121	200	135.78
4	5	1	200	100.00
4	6	1	200	100.00

Data set: British Columbia

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	10.00
1	2	21	100	67.31
1	3	101	140	110.93
1	4	141	260	213.41
1	5	1	260	130.00
1	6	1	260	130.00
2	1	1	20	10.00
2	2	21	90	56.14
2	3	91	140	104.58
2	4	141	260	196.41
2	5	1	260	130.00
2	6	1	260	130.00
3	1	1	20	10.00
3	2	21	80	53.57
3	3	81	140	102.10
3	4	141	260	195.33
3	5	1	260	130.00
3	6	1	260	130.00
4	1	1	20	10.00
4	2	21	100	64.38
4	3	101	140	109.38
4	4	141	260	213.90
4	5	1	260	130.00
4	6	1	260	130.00

Data set: Yukon

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	–1	–1	–1
1	2	–1	–1	–1
1	3	–1	–1	–1
1	4	–1	–1	–1
1	5	–1	–1	–1
1	6	1	150	75
2	1	–1	–1	–1
2	2	–1	–1	–1
2	3	–1	–1	–1
2	4	–1	–1	–1
2	5	–1	–1	–1
2	6	1	150	75
3	1	–1	–1	–1
3	2	–1	–1	–1
3	3	–1	–1	–1
3	4	–1	–1	–1
3	5	–1	–1	–1
3	6	1	150	75
4	1	–1	–1	–1
4	2	–1	–1	–1
4	3	–1	–1	–1
4	4	–1	–1	–1
4	5	–1	–1	–1
4	6	1	150	75

Data set: Northwest Territories

Forest type	Maturity class	Age class (years)		
		Minimum	Maximum	Average
1	1	1	20	10
1	2	21	100	60
1	3	101	160	130
1	4	161	180	170
1	5	1	180	90
1	6	1	180	90
2	1	1	20	10
2	2	21	100	60
2	3	101	160	130
2	4	161	180	170
2	5	1	180	90
2	6	1	180	90
3	1	1	20	10
3	2	21	60	40
3	3	61	80	70
3	4	81	120	100
3	5	1	120	60
3	6	1	120	60
4	1	1	20	10
4	2	21	100	60
4	3	101	160	130
4	4	161	180	170
4	5	1	180	90
4	6	1	180	90

APPENDIX 4
DATA SOURCES FOR DISTURBANCE REGIMES USED IN THE CARBON BUDGET MODEL

Insects

Estimates of areas affected by insects in provincial and national data bases generally account for areas defoliated in successive years. Area estimates for successive years do not necessarily refer to new infestations, but do account for areas that may already have been affected in the previous year. It is therefore difficult to derive an estimate that accounts for infestations that cause stand mortality. Such estimates have been provided by Honer and Bickerstaff (1985). Assistance was given by W.J.A. Volney (personal communication, February 1990) in the distribution of area estimates throughout the ecoclimatic provinces listed below.

Administrative province	Insect affected area ('000 ha)	Proportional distribution by ecoclimatic province			
		Boreal East	Cool Temperate	Cordilleran	Interior Cordilleran
Newfoundland	47.790	1.000	–[a]	–	–
Nova Scotia	49.236	0.950	0.050	–	–
Prince Edward Island	–	–	–	–	–
New Brunswick	17.659	0.400	0.600	–	–
Quebec	145.564	0.800	0.200	–	–
Ontario	98.654	0.984	0.016	–	–
Manitoba	–	–	–	–	–
Saskatchewan	–	–	–	–	–
Alberta	0.503	–	–	1.000	–
British Columbia	28.168	–	–	0.493	0.507
Yukon	–	–	–	–	–
Northwest Territories	–	–	–	–	–

[a] Information not applicable.

Fire

The estimates of annual area burned by ecoclimatic provinces within administrative provinces were provided by B.J. Stocks (personal communications, May 25 and 29, 1990). The distribution by province of area burned in the Cordilleran (150 000 ha) was not provided and was assumed to be proportional to the distribution by province of Cordilleran land area. These data were used for both 1986 and 10-year-average estimates.

	Administrative province (ha)											
Ecoclimatic province	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories
Arctic	–[a]	–	–	–	–	–	–	–	–	–	–	–
Subarctic	17 472	–	–	–	273 560	672	2 462	21 504	–	–	14 784	229 544
Boreal West	–	–	–	–	97 152	–	391 776	668 624	236 544	9 504	1 056	162 096
Boreal East	5 984	–	–	176	–	187 088	–	–	–	–	–	–
Cool Temperate	–	–	–	4 865	90	45	–	–	–	–	–	–
Moderate Temperate	–	–	–	–	–	–	–	–	–	–	–	–
Grassland	–	–	–	–	–	–	8 358	–	642	–	–	–
Subarctic Cordilleran	–	–	–	–	–	–	–	–	–	–	3 000	
Cordilleran	–	–	–	–	–	–	–	–	26 100	80 310	42 090	1 500
Interior Cordilleran	–	–	–	–	–	–	–	–	–	7 000	–	–
Pacific Cordilleran	–	–	–	–	–	–	–	–	–	2 000	–	–
Total area	23 456	0	0	5 041	370 802	187 805	402 596	690 128	263 286	98 814	60 930	393 140

[a] This combination of administrative and ecoclimatic provinces is either nonexistent or has no reported fire.

Prescribed Fires

The estimates of area burned through prescribed burning were provided by B.J. Stocks (personal communications, May 25 and 29, 1990). The distribution by ecoclimatic province was considered to be proportional to the harvest distribution by ecoclimatic province within a province. These data were used for both 1986 and 10-year-average estimates.

British Columbia	Cordilleran	26 354 ha
	Interior Cordilleran	15 884 ha
	Pacific Cordilleran	11 754 ha
Ontario	Cool Temperate	258 ha
	Boreal	4 050 ha

Harvest (Area)

The distribution of area harvested by ecoclimatic province within a province is listed below. Note that the area burned through prescribed burning (disturbance type: clear-cut with slash burn) is included in the estimates of area harvested.

Alberta

Ecoclimatic provinces

Estimate that 50% of harvest occurs in the Boreal and 50% in the Cordilleran.

Area (ha)

Figures estimated from Kuhnke (1989).[1]

1985–1986	Clear-cut (all)
Cordilleran	16 913
Boreal West	16 913
Total	33 825

10-year avg. (1976–1977 to 1985–1986)	Clear-cut
Cordilleran	12 689
Boreal West	12 689
Total	25 377

Note: Totals may not add up due to rounding.

British Columbia

Ecoclimatic provinces
- Pacific Cordilleran: Vancouver
- Interior Cordilleran: Kamloops, Cariboo
- Cordilleran: Prince Rupert, Prince George, Nelson

Area (ha) (crown land only)

Figures calculated from B.C. Forest and Lands annual reports.

1985–1986	Clear-cut	Selective cut
Pacific Cordilleran	44 520	1 969
Interior Cordilleran	60 169	18 224
Cordilleran	99 815	7 033
Total	204 504	27 226

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Pacific Cordilleran	27 196	774
Interior Cordilleran	40 164	16 739
Cordilleran	88 689	8 526
Total	156 049	26 039

Manitoba

Ecoclimatic provinces
- Grassland: southwestern forest region
- Boreal: all other forest regions
- Subarctic: no harvest regions

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut (all)
Grassland	54 (0.34%)
Boreal West	15 846
Total	15 900

The Grassland region produced 0.34% of the 1985–1986 harvest, according to the 1986 Manitoba Department of Natural Resources annual report. Assume an equal volume per hectare throughout the province.

10-year avg. (1976–1977 to 1985–1986)	Clear-cut
Grassland	64 (0.34%)
Boreal West	18 856
Total	18 920

[1] Kuhnke, D.H. 1989. Silviculture statistics for Canada: an 11-year summary. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-301.

New Brunswick

Ecoclimatic provinces

Assume 19.81% of harvesting occurs in the Boreal and 80.19% in the Cool Temperate (proportional to the area covered by ecoclimatic provinces).

Area (ha)

Figures estimated from Kuhnke (1989).

1986	Clear-cut	Selective cut
Boreal East	16 387	862
Cool Temperate	66 333	3 488
Total	82 720	4 350

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Boreal East	16 470	249
Cool Temperate	66 671	1 009
Total	83 141	1 258

Newfoundland

Ecoclimatic province

Boreal

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986 (all clear-cut) = 16 400

Ten-year average (1976–1977 to 1985–1986) = 14 883

Nova Scotia

Ecoclimatic provinces

Assume 54.33% of harvesting occurs in the Cool Temperate and 45.67% in the Boreal (proportional to the area covered by ecoclimatic provinces).

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut	Selective cut
Cool Temperate	15 647	531
Boreal East	13 153	447
Total	28 800	978

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Cool Temperate	16 850	277
Boreal East	14 165	233
Total	31 015	510

Ontario

Ecoclimatic provinces

Boreal: northwestern, north central, northeastern, northern forest regions

Cool Temperate: Algonquin, southwestern, eastern, (0.5) central forest regions

Moderate Temperate: (0.5) central forest region

Area and volume harvested assumptions based on 1986 harvesting data by forest region from the Ontario Ministry of Natural Resources annual statistical reports.

Distribution	
Boreal East	94%
Cool Temperate	6%
Moderate Temperate	0%

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut	Selective cut
Boreal East	174 062	30 843
Cool Temperate	11 110	1 969
Total	185 172	32 812

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Boreal East	158 248	36 379
Cool Temperate	10 101	2 322
Total	168 349	38 701

Prince Edward Island

Ecoclimatic province

Cool Temperate

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut (all)
Cool Temperate	3 200

10-year avg. (1976–1977 to 1985–1986)	Clear-cut (all)
Cool Temperate	2 268

Quebec

Ecoclimatic provinces

Boreal: Bas-Saint-Laurent/Gaspesie, Saguenay/Lac Saint-Jean, Quebec, Abitibi-Temiscamingue, Côte-Nord

Cool Temperate: Mauricie, Estrie, Montreal, Ottawa

Area- and volume-harvested assumptions based on 1988 harvesting data by forest region (R. Lamarre, personal communication, 1990).

Distribution (percentage of total 1988 harvest)

1985–1986	Clear-cut	Selective cut
Boreal East	85%	38%
Cool Temperate	15%	62%

Area (ha) (crown land only)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut	Selective cut
Boreal East	205 827	9 131
Cool Temperate	36 323	14 899
Total	242 150	24 030

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Boreal East	168 661	13 974
Cool Temperate	29 764	22 800
Total	198 425	36 774

Saskatchewan

Ecoclimatic provinces

Assume all harvesting occurs in the Boreal ecoclimatic province.

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut (all)
Boreal West	19 963

10-year avg. (1976–1977 to 1985–1986)	Clear-cut
Boreal West	19 163

Northwest Territories

Ecoclimatic provinces

Assume 97% of harvesting occurs in the Boreal and 3% in the Cordilleran (proportional to the area covered by ecoclimatic provinces).

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut (all)
Boreal West	960
Cordilleran	30
Total	990

10-year avg. (1976–1977 to 1985–1986)	Clear-cut
Boreal West	719
Cordilleran	22
Total	741

Yukon

Ecoclimatic provinces

Assume 2% of harvesting occurs in the Boreal, 92% in the Cordilleran, and 6% in the Pacific Cordilleran.

Area (ha)

Figures estimated from Kuhnke (1989).

1985–1986	Clear-cut (all)
Boreal West	3
Cordilleran	124
Pacific Cordilleran	8
Total	135

10-year avg. (1976–1977 to 1985–1986)	Clear-cut	Selective cut
Boreal West	4	5
Cordilleran	167	218
Pacific Cordilleran	11	14
Total	182	237

APPENDIX 5
DISTURBANCE MATRICES FOR FIVE DISTURBANCE TYPES

Disturbance matrices for each of the five disturbance types are shown in this appendix. These matrices describe the C transfer at the time of disturbance among pools (sources in rows and sinks in columns) (see page 19). The sum of each row adds up to unity, thus ensuring conservation of carbon. There are 10 different matrices for wildfires in different ecoclimatic provinces, and six different matrices for clear-cut logging and slash burning. For each of the remaining three disturbance types, matrices do not differ between ecoclimatic provinces. Only one matrix for every disturbance type is included.

Disturbance matrix: wildfire

Source[a]	Sink[a] (proportion of carbon transferred)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.197	–[b]	–	–	–	–	–	–	0.099	0.346	0.049	–	0.278	0.028	0.003	–
2	–	0.185	–	–	–	–	–	–	0.093	–	–	–	0.619	0.094	0.009	–
3	–	–	0.194	–	–	–	–	–	0.097	0.194	–	–	0.464	0.464	0.005	–
4	–	–	–	0.196	–	–	–	–	0.196	0.196	–	–	0.361	0.046	0.005	–
5	–	–	–	–	0.197	–	–	–	0.099	0.346	0.049	–	0.278	0.028	0.003	–
6	–	–	–	–	–	0.185	–	–	0.093	–	–	–	0.619	0.094	0.009	–
7	–	–	–	–	–	–	0.194	–	0.097	0.194	–	–	0.464	0.046	0.005	–
8	–	–	–	–	–	–	–	0.196	0.196	0.196	–	–	0.361	0.046	0.005	–
9	–	–	–	–	–	–	–	–	0.520	0.087	0.087	–	0.275	0.028	0.003	–
10	–	–	–	–	–	–	–	–	–	0.752	0.094	–	0.138	0.014	0.002	–
11	–	–	–	–	–	–	–	–	–	–	0.923	–	0.061	0.014	0.002	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[b] Zero value.

Disturbance matrix: insects causing stand mortality

Source[a]	Sink[a] (proportion of carbon transferred) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.200	–[b]	–	–	–	–	–	–	0.100	0.700	–	–	–	–	–	–
2	–	0.200	–	–	–	–	–	–	0.600	0.100	–	–	0.100	–	–	–
3	–	–	0.200	–	–	–	–	–	0.100	0.700	–	–	–	–	–	–
4	–	–	–	1.000	–	–	–	–	–	–	–	–	–	–	–	–
5	–	–	–	–	0.200	–	–	–	0.100	0.700	–	–	–	–	–	–
6	–	–	–	–	–	0.200	–	–	0.600	0.100	–	–	0.100	–	–	–
7	–	–	–	–	–	–	0.200	–	0.100	0.700	–	–	–	–	–	–
8	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–
11	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[b] Zero value.

Disturbance matrix: clear-cut logging with slash burning

Source[a]	Sink[a] (proportion of carbon transferred)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.017	–[b]	–	–	–	–	–	–	0.042	0.018	0.009	–	0.101	0.012	0.001	0.800
2	–	0.166	–	–	–	–	–	–	0.331	0.033	0.016	–	0.407	0.043	0.004	–
3	–	–	0.166	–	–	–	–	–	0.331	0.033	0.016	–	0.407	0.043	0.004	–
4	–	–	–	0.364	–	–	–	–	0.242	0.122	–	–	0.237	0.031	0.004	–
5	–	–	–	–	0.017	–	–	–	0.042	0.018	0.009	–	0.101	0.012	0.001	0.800
6	–	–	–	–	–	0.166	–	–	0.331	0.033	0.016	–	0.407	0.043	0.004	–
7	–	–	–	–	–	–	0.166	–	0.331	0.033	0.016	–	0.407	0.043	0.004	–
8	–	–	–	–	–	–	–	0.364	0.242	0.122	–	–	0.237	0.031	0.004	–
9	–	–	–	–	–	–	–	–	0.714	–	–	–	0.257	0.026	0.003	–
10	–	–	–	–	–	–	–	–	–	0.857	–	–	0.128	0.013	0.002	–
11	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[b] Zero value.

Disturbance matrix: clear-cut logging

Source[a]	Sink[a] (proportion of carbon transferred) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	–[b]	–	–	–	–	–	–	–	–	0.150	–	–	–	–	–	0.850
2	–	0.100	–	–	–	–	–	–	0.900	–	–	–	–	–	–	–
3	–	–	0.100	–	–	–	–	–	0.800	0.100	–	–	–	–	–	–
4	–	–	–	0.500	–	–	–	–	0.400	0.100	–	–	–	–	–	–
5	–	–	–	–	–	–	–	–	–	0.150	–	–	–	–	–	0.850
6	–	–	–	–	–	0.100	–	–	0.900	–	–	–	–	–	–	–
7	–	–	–	–	–	–	0.100	–	0.800	0.100	–	–	–	–	–	–
8	–	–	–	–	–	–	–	0.500	0.400	0.100	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–
11	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[b] Zero value.

Disturbance matrix: partial cutting

Source[a]	Sink[a] (proportion of carbon transferred)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.100	–[b]	–	–	–	–	–	–	–	0.050	–	–	–	–	–	0.850
2	–	0.100	–	–	–	–	–	–	0.900	–	–	–	–	–	–	–
3	–	–	0.100	–	–	–	–	–	0.750	0.150	–	–	–	–	–	–
4	–	–	–	0.700	–	–	–	–	0.250	0.050	–	–	–	–	–	–
5	–	–	–	–	0.100	–	–	–	–	0.050	–	–	–	–	–	0.850
6	–	–	–	–	–	0.100	–	–	0.900	–	–	–	–	–	–	–
7	–	–	–	–	–	–	0.100	–	0.750	0.150	–	–	–	–	–	–
8	–	–	–	–	–	–	–	0.700	0.250	0.050	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–	–
11	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–	–
12	–	–	–	–	–	–	–	–	–	–	–	1.000	–	–	–	–

[a] 1 = Softwood merchantable stem.
2 = Softwood foliage.
3 = Softwood other merchantable.
4 = Softwood submerchantable.
5 = Hardwood merchantable stem.
6 = Hardwood foliage.
7 = Hardwood other merchantable.
8 = Hardwood submerchantable.
9 = Soil fast C pool.
10 = Soil medium C pool.
11 = Soil slow C pool.
12 = Not used.
13 = CO_2.
14 = CO.
15 = CH_4.
16 = Forest products sector.

[b] Zero value.

APPENDIX 6
PARAMETER VALUES FOR THE FOREST PRODUCT SECTOR, AND HISTORIC CUTTING PARAMETERS FOR THE CARBON BUDGET MODEL

PARAMETERS AND DATA VALUES OF THE FOREST PRODUCT SECTOR SUBMODEL

Miscellaneous parameters of forest product conversion

Chipping efficiency (by proportion):	0.85
Proportion chips decomposing in storage (by proportion):	0.05
Carbon conversion factor (t C 1000 m^{-3}):	250

Proportional fates of different outputs from pulping processes

Pulping process output	Fate of pulping process output				
	Pulp	Burned: Waste	Burned: Energy	Landfill	Rapid decomposition
Sulfite	0.500	0.500	0.000	0.000	0.000
Kraft	0.400	0.600	0.000	0.000	0.000
CTMP[a]	0.850	0.000	0.000	0.075	0.075
Stone-ground wood	0.950	0.000	0.000	0.025	0.025

[a] CTMP = chemithermomechanical pulp.

Proportional fates of culling waste and hog fuel

Pulping process waste product	Fate of pulping process waste product			
	Burned: Waste	Burned: Energy	Landfill	Rapid decomposition
Culling waste	0.670	0.330	0.000	0.000
Hog fuel	1.000	0.000	0.000	0.000

Proportional emissions by gas type and process

Emission process	Gas emission		
	Carbon dioxide	Methane	Carbon monoxide
Waste burning	1	0	0
Energy burning	1	0	0
Decomposition	0	1	0

Proportional fates of the three forest product types

Forest product type	Fate of forest product type: Burned – Waste	Burned – Energy	Landfill	Decomposition	Recycling
Construction lumber	0.030	0.020	0.850	0.050	0.050
Other lumber	0.030	0.020	0.850	0.050	0.050
Pulp products	0.025	0.020	0.900	0.005	0.050

Proportional distribution of wood processed by the pulping method

Administrative province	Sulfite	Kraft	CTMP[a]	Stone-ground wood
Newfoundland	0.20	0.00	0.80	0.00
Nova Scotia	0.59	0.00	0.10	0.31
Prince Edward Island	0.23	0.33	0.25	0.19
New Brunswick	0.23	0.33	0.25	0.19
Quebec	0.11	0.44	0.25	0.20
Ontario	0.09	0.55	0.17	0.19
Manitoba	0.15	0.64	0.00	0.21
Saskatchewan	0.00	1.00	0.00	0.00
Alberta	0.00	0.84	0.16	0.00
British Columbia	0.00	0.74	0.20	0.06
Yukon	0.00	0.00	0.00	0.00
Northwest Territories	0.00	0.00	0.00	0.00

[a] CTMP = chemithermomechanical pulp.

Proportional distribution of harvest in ecoclimatic provinces

Administrative province	Ecoclimatic province: 1[a]	2	3	4	5	6	7	8	9	10	11
Newfoundland	–[b]	–	–	1.00	–	–	–	–	–	–	–
Nova Scotia	–	–	–	0.46	0.54	–	–	–	–	–	–
Prince Edward Island	–	–	–	–	1.00	–	–	–	–	–	–
New Brunswick	–	–	–	0.20	0.80	–	–	–	–	–	–
Quebec	–	–	–	0.81	0.19	–	–	–	–	–	–
Ontario	–	–	–	0.94	0.06	–	–	–	–	–	–
Manitoba	–	–	1.00	–	–	–	–	–	–	–	–
Saskatchewan	–	–	1.00	–	–	–	–	–	–	–	–
Alberta	–	–	0.50	–	–	–	–	–	0.50	–	–
British Columbia	–	–	–	–	–	–	–	–	0.46	0.34	0.20
Yukon	–	–	0.02	–	–	–	–	–	0.92	–	0.06
Northwest Territories	–	–	0.97	–	–	–	–	–	0.03	–	–

[a] 1 = Arctic; 2 = Subarctic; 3 = Boreal West; 4 = Boreal East; 5 = Cool Temperate; 6 = Moderate Temperate; 7 = Grassland; 8 = Subarctic Cordilleran; 9 = Cordilleran; 10 = Interior Cordilleran; 11 = Pacific Cordilleran.

[b] This combination of administrative and ecoclimatic provinces is either nonexistent or has no reported harvest.

Historic proportions of wood meeting various fates after cutting for each year of the simulation

Year of simulation	Construction lumber		Other lumber		Burned as waste		Burned for fuel		Landfill		Pulp	
	SW	HW[a]	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW
1986	0.315	0.000	0.190	0.300	0.165	0.280	0.083	0.070	0.000	0.000	0.248	0.350
1985	0.313	0.000	0.188	0.300	0.168	0.280	0.084	0.070	0.000	0.000	0.248	0.350
1984	0.311	0.000	0.186	0.300	0.170	0.280	0.085	0.070	0.000	0.000	0.248	0.350
1983	0.310	0.000	0.183	0.300	0.173	0.280	0.086	0.070	0.000	0.000	0.248	0.350
1982	0.308	0.000	0.181	0.300	0.176	0.280	0.088	0.070	0.000	0.000	0.248	0.350
1981	0.306	0.000	0.179	0.300	0.195	0.280	0.097	0.070	0.000	0.000	0.223	0.350
1980	0.304	0.000	0.177	0.300	0.214	0.280	0.107	0.070	0.000	0.000	0.198	0.350
1979	0.302	0.000	0.175	0.300	0.233	0.280	0.117	0.070	0.000	0.000	0.173	0.350
1978	0.301	0.000	0.173	0.300	0.252	0.280	0.126	0.070	0.000	0.000	0.149	0.350
1977	0.299	0.000	0.170	0.300	0.271	0.280	0.136	0.070	0.000	0.000	0.124	0.350
1976	0.297	0.000	0.168	0.300	0.290	0.280	0.145	0.070	0.000	0.000	0.099	0.350
1975	0.295	0.000	0.166	0.300	0.310	0.280	0.155	0.070	0.000	0.000	0.074	0.350
1974	0.293	0.000	0.164	0.300	0.329	0.280	0.164	0.070	0.000	0.000	0.050	0.350
1973	0.292	0.000	0.162	0.300	0.348	0.280	0.174	0.070	0.000	0.000	0.025	0.350
1972	0.290	0.000	0.159	0.300	0.367	0.280	0.184	0.070	0.000	0.000	0.000	0.350
1971	0.288	0.000	0.157	0.300	0.370	0.280	0.185	0.070	0.000	0.000	0.000	0.350
1970	0.286	0.000	0.155	0.300	0.372	0.280	0.186	0.070	0.000	0.000	0.000	0.350
1969	0.284	0.000	0.153	0.300	0.375	0.280	0.188	0.070	0.000	0.000	0.000	0.350
1968	0.283	0.000	0.151	0.300	0.378	0.280	0.189	0.070	0.000	0.000	0.000	0.350
1967	0.281	0.000	0.149	0.300	0.380	0.280	0.190	0.070	0.000	0.000	0.000	0.350
1966	0.279	0.000	0.146	0.300	0.383	0.280	0.192	0.070	0.000	0.000	0.000	0.350
1965	0.277	0.000	0.144	0.300	0.386	0.280	0.193	0.070	0.000	0.000	0.000	0.350
1964	0.276	0.000	0.142	0.300	0.388	0.280	0.194	0.070	0.000	0.000	0.000	0.350
1963	0.274	0.000	0.140	0.300	0.391	0.280	0.196	0.070	0.000	0.000	0.000	0.350
1962	0.272	0.000	0.138	0.300	0.394	0.280	0.197	0.070	0.000	0.000	0.000	0.350
1961	0.270	0.000	0.136	0.300	0.396	0.280	0.198	0.070	0.000	0.000	0.000	0.350
1960	0.268	0.000	0.133	0.300	0.399	0.280	0.199	0.070	0.000	0.000	0.000	0.350
1959	0.267	0.000	0.131	0.300	0.401	0.280	0.201	0.070	0.000	0.000	0.000	0.350
1958	0.265	0.000	0.129	0.300	0.404	0.280	0.202	0.070	0.000	0.000	0.000	0.350
1957	0.263	0.000	0.127	0.300	0.407	0.280	0.203	0.070	0.000	0.000	0.000	0.350
1956	0.261	0.000	0.125	0.300	0.409	0.280	0.205	0.070	0.000	0.000	0.000	0.350
1955	0.259	0.000	0.122	0.300	0.412	0.280	0.206	0.070	0.000	0.000	0.000	0.350
1954	0.258	0.000	0.120	0.300	0.415	0.280	0.207	0.070	0.000	0.000	0.000	0.350
1953	0.256	0.000	0.118	0.300	0.417	0.280	0.209	0.070	0.000	0.000	0.000	0.350
1952	0.254	0.000	0.116	0.300	0.420	0.280	0.210	0.070	0.000	0.000	0.000	0.350
1951	0.252	0.000	0.114	0.300	0.423	0.280	0.211	0.070	0.000	0.000	0.000	0.350
1950	0.250	0.000	0.112	0.300	0.425	0.280	0.213	0.070	0.000	0.000	0.000	0.350
1949	0.249	0.000	0.109	0.300	0.428	0.280	0.214	0.070	0.000	0.000	0.000	0.350
1948	0.247	0.000	0.107	0.300	0.431	0.280	0.215	0.070	0.000	0.000	0.000	0.350
1947	0.245	0.000	0.105	0.300	0.433	0.280	0.217	0.070	0.000	0.000	0.000	0.350

[a] SW = softwood; HW = hardwood.

Distribution and Historic Volumes: Newfoundland

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.098	0.736	0.166
Hardwoods	0.042	0.012	0.946

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m³) Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	67.50	166.50	1732.00	442.00
1985	2	48.77	142.23	1760.00	558.00
1984	3	2.10	184.90	2053.00	649.00
1983	4	6.77	291.23	1697.00	434.00
1982	5	2.23	153.77	1736.00	487.00
1981	6	6.81	262.19	1903.00	396.00
1980	7	6.67	330.33	2189.00	269.00
1979	8	4.85	281.15	1968.00	227.00
1978	9	2.38	266.62	1909.00	110.00
1977	10	4.21	233.79	1875.00	82.00
1976	11	4.45	222.55	2011.00	107.00
1975	12	2.19	151.81	2195.00	104.00
1974	13	4.41	187.59	2874.00	145.00
1973	14	4.17	243.83	2563.00	142.00
1972	15	2.05	151.95	2071.00	130.00
1971	16	2.07	152.93	2013.00	156.00
1970	17	0.00	174.00	2527.00	147.00
1969	18	2.19	156.65	2073.27	123.90
1968	19	2.19	156.98	2077.67	124.16
1967	20	2.27	162.63	2152.47	128.63
1966	21	3.56	255.52	3381.82	202.10
1965	22	2.60	186.04	2462.22	147.14
1964	23	2.54	182.25	2412.06	144.15
1963	24	2.34	167.55	2217.59	132.53
1962	25	1.96	140.42	1858.55	111.07
1961	26	2.57	184.51	2441.98	145.94
1960	27	3.33	238.56	2157.42	188.69
1959	28	2.54	182.05	2409.42	143.99
1958	29	2.21	158.11	2092.63	125.06
1957	30	2.57	183.91	2434.06	145.46
1956	31	2.76	197.67	2616.22	156.35
1955	32	2.95	211.63	2801.02	167.39
1954	33	2.62	188.10	2489.50	148.78
1953	34	2.99	214.43	2837.98	169.60
1952	35	2.69	192.62	2549.34	152.35
1951	36	3.18	227.79	3014.86	180.17
1950	37	2.96	211.97	2805.42	167.65
1949	38	2.55	182.98	2421.74	144.73
1948	39	0.00	0.00	0.00	0.00
1947	40	0.00	0.00	0.00	0.00

Distribution and Historic Volumes: Nova Scotia

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.312	0.672	0.016
Hardwoods	0.078	0.470	0.452

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3) Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	68.37	993.63	2471.00	326.00
1985	2	109.73	844.27	2190.00	296.00
1984	3	32.38	960.62	2270.00	296.00
1983	4	39.49	888.51	2397.00	296.00
1982	5	48.45	746.55	1943.00	263.00
1981	6	55.43	859.57	2795.00	277.00
1980	7	39.36	931.64	3310.00	263.00
1979	8	47.98	1025.02	3098.00	218.00
1978	9	24.19	960.81	2968.00	204.00
1977	10	26.15	921.85	2540.00	187.00
1976	11	130.88	946.12	2265.00	212.00
1975	12	228.55	821.45	2508.00	181.00
1974	13	333.17	1001.83	2792.00	169.00
1973	14	26.52	1014.48	2394.00	159.00
1972	15	26.31	942.69	2144.00	145.00
1971	16	26.45	793.55	2263.00	153.00
1970	17	26.85	1038.15	2022.00	157.00
1969	18	27.59	948.85	2300.48	155.08
1968	19	29.48	1003.59	2433.20	164.03
1967	20	24.33	836.88	2029.01	136.78
1966	21	24.63	847.11	2053.81	138.45
1965	22	24.31	836.05	2026.99	136.65
1964	23	23.81	818.91	1985.44	133.84
1963	24	19.71	677.91	1643.58	110.80
1962	25	18.64	641.14	1554.43	104.79
1961	26	22.01	756.98	1835.29	123.72
1960	27	22.33	768.04	1862.10	125.53
1959	28	20.39	701.41	1700.56	114.64
1958	29	19.12	657.73	1594.65	107.50
1957	30	23.88	821.12	1990.80	134.21
1956	31	25.31	870.61	2110.78	142.29
1955	32	27.00	928.39	2250.88	151.74
1954	33	23.08	793.75	1924.44	129.73
1953	34	24.61	846.28	2051.80	138.32
1952	35	26.83	922.86	2237.47	150.83
1951	36	29.45	1012.99	2455.99	165.57
1950	37	26.57	913.74	2215.35	149.34
1949	38	23.74	816.42	1979.40	133.44
1948	39	28.66	985.62	2389.63	161.09
1947	40	31.80	1093.72	2651.72	178.76

Distribution and Historic Volumes: Prince Edward Island

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.467	0.193	0.340
Hardwoods	0.023	0.005	0.972

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3) Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	0.00	114.00	46.00	316.00
1985	2	0.00	85.00	43.00	287.00
1984	3	0.00	84.00	42.00	287.00
1983	4	0.00	107.00	31.00	156.00
1982	5	13.75	63.25	48.00	150.00
1981	6	21.67	108.33	59.00	144.00
1980	7	5.37	96.63	91.00	85.00
1979	8	16.80	79.20	48.00	79.00
1978	9	16.21	60.79	45.00	37.00
1977	10	0.00	68.00	37.00	34.00
1976	11	0.00	74.00	48.00	42.00
1975	12	0.00	77.00	45.00	45.00
1974	13	22.75	68.25	62.00	37.00
1973	14	0.00	79.00	62.00	31.00
1972	15	0.00	72.00	66.00	51.00
1971	16	8.06	77.94	66.00	60.00
1970	17	0.00	78.00	109.00	57.00
1969	18	5.78	70.42	68.51	44.29
1968	19	4.93	59.99	58.36	37.73
1967	20	5.11	62.22	60.53	39.14
1966	21	5.78	70.42	68.51	44.29
1965	22	5.78	70.42	68.51	44.29
1964	23	5.26	64.08	62.34	40.31
1963	24	5.17	62.97	61.26	39.61
1962	25	4.74	57.75	56.18	36.33
1961	26	8.81	107.30	104.39	67.50
1960	27	9.33	113.64	110.55	71.48
1959	28	9.18	111.77	108.74	70.31
1958	29	9.18	111.77	108.74	70.31
1957	30	7.86	95.75	93.15	60.23
1956	31	8.90	108.42	105.48	68.20
1955	32	9.79	119.23	115.99	75.00
1954	33	7.86	95.75	93.15	60.23
1953	34	8.66	105.44	102.58	66.32
1952	35	10.56	128.54	125.05	80.85
1951	36	9.52	115.87	112.73	72.89
1950	37	8.57	104.32	101.49	65.62
1949	38	8.38	102.09	99.31	64.21
1948	39	8.75	106.56	103.66	67.03
1947	40	9.42	114.76	111.64	72.18

Distribution and Historic Volumes: New Brunswick

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.324	0.669	0.007
Hardwoods	0.151	0.590	0.259

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3) Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	87.42	2547.58	5745.00	340.00
1985	2	141.18	2291.82	5126.00	337.00
1984	3	135.33	2487.67	4586.00	269.00
1983	4	134.50	2290.50	4752.00	265.00
1982	5	146.93	1976.07	3956.00	241.00
1981	6	150.95	2213.05	5165.00	266.00
1980	7	154.28	2266.72	5714.00	252.00
1979	8	154.56	2252.44	6088.00	255.00
1978	9	141.23	2216.77	5947.00	204.00
1977	10	159.92	1822.08	5550.00	170.00
1976	11	203.56	1682.44	5395.00	198.00
1975	12	187.94	1612.06	4913.00	193.00
1974	13	213.47	1771.53	6626.00	170.00
1973	14	342.72	2112.28	6258.00	156.00
1972	15	194.13	1685.87	5167.00	179.00
1971	16	199.63	1602.37	4913.00	190.00
1970	17	276.95	1627.05	4712.00	199.00
1969	18	212.79	1526.10	4800.06	155.05
1968	19	214.35	1537.27	4835.20	156.19
1967	20	183.45	1315.67	4138.21	133.67
1966	21	191.37	1372.44	4316.76	139.44
1965	22	175.82	1260.96	3966.11	128.11
1964	23	175.98	1262.09	3969.69	128.23
1963	24	178.49	1280.11	4026.34	130.06
1962	25	126.55	907.59	2854.65	92.21
1961	26	174.01	1247.96	3925.24	126.79
1960	27	168.61	209.20	3803.33	122.86
1959	28	155.38	1114.36	3505.03	113.22
1958	29	155.00	1111.63	3496.43	112.94
1957	30	181.67	1302.90	4098.05	132.38
1956	31	232.79	1669.49	5251.10	169.62
1955	32	182.37	1307.92	4113.83	132.89
1954	33	158.34	1135.57	3571.72	115.38
1953	34	171.94	1233.14	3878.63	125.29
1952	35	201.38	1444.25	4542.63	146.74
1951	36	253.96	1821.33	5728.67	185.05
1950	37	179.22	1285.35	4042.84	130.59
1949	38	170.04	1219.46	3835.60	123.90
1948	39	218.74	1568.73	4934.15	159.38
1947	40	221.91	1591.53	5005.86	161.70

Distribution and Historic Volumes: Quebec

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.612	0.374	0.014
Hardwoods	0.247	0.325	0.428

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	1 048.70	20 475.30	14 002.00	2 601.00
1985	2	853.39	18 474.61	13 514.00	2 558.00
1984	3	1 041.42	18 614.58	14 329.00	2 534.00
1983	4	770.29	20 119.71	12 998.00	2 400.00
1982	5	1 060.90	15 519.10	10 316.00	2 237.00
1981	6	817.26	16 229.74	14 979.00	2 208.00
1980	7	1 498.46	15 802.54	12 318.00	2 667.00
1979	8	1 118.25	18 448.75	14 045.00	2 124.00
1978	9	1 563.46	17 408.54	13 096.00	2 011.00
1977	10	1 133.42	15 516.58	12 601.00	1 812.00
1976	11	1 335.62	12 284.38	13 598.00	1 840.00
1975	12	1 145.32	10 300.68	15 149.00	1 812.00
1974	13	1 658.03	10 820.96	18 548.00	1 685.00
1973	14	1 433.04	9 906.96	16 310.00	1 699.00
1972	15	1 318.32	9 486.68	15 350.00	1 690.00
1971	16	1 153.87	8 366.13	15 291.00	1 770.00
1970	17	1 106.86	7 922.14	17 740.00	2 129.00
1969	18	1 377.38	9 602.84	17 188.85	1 852.92
1968	19	1 280.35	8 926.34	15 977.93	1 722.39
1967	20	1 298.93	9 055.88	16 209.81	1 747.39
1966	21	1 291.49	9 004.07	16 117.05	1 737.39
1965	22	1 215.75	8 475.98	15 171.79	1 635.49
1964	23	1 212.35	8 452.31	15 129.42	1 630.92
1963	24	1 186.89	8 274.78	14 811.66	1 596.67
1962	25	1 138.17	7 935.09	14 203.62	1 531.12
1961	26	1 187.67	8 280.22	14 821.39	1 597.72
1960	27	1 143.26	7 970.60	14 267.17	1 537.97
1959	28	1 139.73	7 945.97	14 223.09	1 533.22
1958	29	1 061.27	7 399.01	13 244.04	1 427.68
1957	30	1 176.38	8 201.54	14 680.55	1 582.53
1956	31	1 395.46	9 728.87	17 414.43	1 877.24
1955	32	1 320.40	9 205.58	16 477.76	1 776.27
1954	33	1 304.75	9 096.51	16 282.52	1 755.22
1953	34	1 223.27	8 528.43	15 265.68	1 645.61
1952	35	1 292.69	9 012.38	16 131.94	1 738.99
1951	36	1 483.27	10 341.08	18 510.28	1 995.37
1950	37	1 271.22	8 862.69	15 863.99	1 710.11
1949	38	1 114.13	7 767.49	13 903.61	1 498.78
1948	39	1 369.86	9 550.39	17 094.96	1 842.80
1947	40	1 369.86	9 550.39	17 094.96	1 842.80

Distribution and Historic Volumes: Ontario

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.486	0.499	0.015
Hardwoods	0.238	0.464	0.298

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	1 370.18	11 647.82	14 841.00	2 32 7.00
1985	2	1 101.70	11 143.30	13 805.00	2 175.00
1984	3	1 584.60	10 743.40	13 631.00	2 171.00
1983	4	1 131.35	7 983.65	12 450.00	2 171.00
1982	5	1 074.64	6 672.36	10 222.00	1 809.00
1981	6	995.17	7 838.83	12 105.00	1 869.00
1980	7	1 229.91	7 944.09	10 803.00	1 345.00
1979	8	1 127.43	8 137.57	10 769.00	1 260.00
1978	9	1 230.16	7 163.84	10 604.00	1 189.00
1977	10	1 160.95	6 910.05	10 306.00	892.00
1976	11	1 354.08	6 200.93	9 401.00	920.00
1975	12	926.05	4 482.95	7 929.00	878.00
1974	13	1 285.25	4 881.75	11 893.00	807.00
1973	14	1 363.08	5 196.92	11 142.00	742.00
1972	15	1 377.01	4 911.99	10 349.00	732.00
1971	16	1 148.66	4 439.34	9 472.00	778.00
1970	17	1 362.62	4 007.38	10 638.00	793.00
1969	18	1 317.80	4 725.05	10 784.57	776.58
1968	19	1 252.90	4 492.34	10 253.43	738.33
1967	20	1 287.04	4 614.74	10 532.78	758.45
1966	21	1 273.86	4 567.50	10 424.96	750.68
1965	22	1 202.22	4 310.63	9 838.68	708.46
1964	23	1 207.99	4 331.30	9 885.85	711.86
1963	24	1 134.40	4 067.45	9 283.65	668.50
1962	25	1 101.09	3 948.01	9 011.03	648.87
1961	26	1 047.27	3 755.03	8 570.56	617.15
1960	27	1 147.50	4 114.43	9 390.86	676.22
1959	28	1 126.77	4 040.08	9 221.16	664.00
1958	29	1 025.03	3 675.31	8 388.61	604.05
1957	30	1 197.81	4 294.80	9 802.54	705.86
1956	31	1 160.45	4 160.86	9 496.84	683.85
1955	32	1 149.00	4 119.79	9 403.11	677.10
1954	33	1 054.23	3 779.99	8 627.53	621.25
1953	34	1 068.90	3 832.60	8 747.60	629.90
1952	35	1 196.31	4 289.43	9 790.28	704.98
1951	36	1 272.81	4 563.74	10 416.38	750.06
1950	37	1 094.50	3 924.39	8 957.12	644.99
1949	38	965.67	3 462.46	7 902.80	569.07
1948	39	1 198.18	4 296.14	9 805.60	706.08
1947	40	1 258.22	4 511.40	10 296.92	741.46

Distribution and Historic Volumes: Manitoba

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.405	0.581	0.014
Hardwoods	0.175	0.036	0.789

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	23.78	639.22	927.00	113.00
1985	2	12.65	515.35	1065.00	124.00
1984	3	90.87	289.13	1202.00	116.00
1983	4	106.60	458.40	840.00	115.00
1982	5	71.84	512.16	790.00	124.00
1981	6	83.36	513.64	1104.00	102.00
1980	7	100.32	669.68	1458.00	107.00
1979	8	113.55	599.45	1085.00	105.00
1978	9	87.96	645.04	937.00	133.00
1977	10	65.53	628.47	948.00	142.00
1976	11	60.88	633.12	878.00	170.00
1975	12	88.95	503.05	1274.00	156.00
1974	13	65.09	549.91	1321.00	165.00
1973	14	127.14	656.86	886.00	152.00
1972	15	146.84	549.16	954.00	182.00
1971	16	100.01	396.99	873.00	185.00
1970	17	132.79	272.21	664.00	184.00
1969	18	100.04	424.25	821.86	151.85
1968	19	72.19	306.15	593.08	109.58
1967	20	67.85	287.74	557.42	102.99
1966	21	82.08	348.07	674.28	124.58
1965	22	80.34	340.70	660.01	121.94
1964	23	74.46	315.78	611.73	113.02
1963	24	478.67	333.62	646.30	119.41
1962	25	100.58	426.51	826.25	152.66
1961	26	71.06	301.34	583.75	107.85
1960	27	85.62	363.08	703.36	129.95
1959	28	97.97	415.47	804.85	148.70
1958	29	95.30	404.14	782.91	144.65
1957	30	114.00	483.44	936.53	173.03
1956	31	127.09	538.95	1044.06	192.90
1955	32	106.99	453.70	878.92	162.39
1954	33	117.21	497.03	962.86	177.90
1953	34	114.20	484.29	938.17	173.34
1952	35	143.72	609.47	1180.67	218.14
1951	36	164.15	696.13	1348.56	249.16
1950	37	107.59	456.25	883.86	163.30
1949	38	108.72	461.07	893.19	165.02
1948	39	128.96	546.88	1059.42	195.74
1947	40	126.69	537.25	1040.77	192.29

Distribution and Historic Volumes: Saskatchewan

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.688	0.276	0.036
Hardwoods	0.064	0.764	0.172

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	0.00	2146.00	1193.00	190.00
1985	2	0.00	1811.00	1056.00	150.00
1984	3	0.00	1270.00	1323.00	133.00
1983	4	0.00	1087.00	1396.00	129.00
1982	5	26.27	1477.73	898.00	124.00
1981	6	44.37	1778.63	1605.00	127.00
1980	7	83.09	1558.91	1569.00	119.00
1979	8	25.74	1879.26	1549.00	125.00
1978	9	31.96	1701.04	974.00	156.00
1977	10	59.91	1993.09	722.00	184.00
1976	11	19.69	1274.31	1345.00	227.00
1975	12	0.00	787.00	1305.00	221.00
1974	13	12.18	867.82	1687.00	210.00
1973	14	31.21	1086.79	1356.00	244.00
1972	15	0.00	1147.00	1308.00	184.00
1971	16	0.00	809.00	1231.00	252.00
1970	17	0.00	867.00	1253.00	256.00
1969	18	7.88	867.67	1241.32	208.13
1968	19	6.20	682.57	976.50	163.73
1967	20	6.19	681.45	974.90	163.46
1966	21	4.45	490.37	701.55	117.63
1965	22	4.36	479.55	686.06	115.03
1964	23	3.78	416.11	595.30	99.81
1963	24	4.04	444.85	636.41	106.70
1962	25	4.59	504.93	722.37	121.12
1961	26	4.22	465.00	665.24	111.54
1960	27	4.79	527.32	754.40	126.49
1959	28	4.28	471.34	674.32	113.06
1958	29	3.99	439.62	628.94	105.45
1957	30	5.29	582.18	832.89	139.65
1956	31	5.59	615.02	879.87	147.52
1955	32	5.30	583.30	834.49	139.92
1954	33	6.27	690.03	987.18	165.52
1953	34	6.88	757.58	1083.82	181.72
1952	35	6.88	757.58	1083.82	181.72
1951	36	7.03	773.63	1106.78	185.57
1950	37	6.77	744.89	1065.67	178.68
1949	38	6.36	700.48	1002.13	168.02
1948	39	7.89	868.42	1242.39	208.31
1947	40	8.61	947.91	1356.11	227.37

Distribution and Historic Volumes: Alberta

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.908	0.086	0.006
Hardwoods	0.084	0.882	0.034

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	0.00	8600.00	1698.00	89.00
1985	2	0.00	6839.00	2041.00	99.00
1984	3	328.70	6314.00	1715.00	99.00
1983	4	173.56	5544.00	1529.00	126.00
1982	5	49.85	4354.15	1175.00	133.00
1981	6	49.29	4996.71	1489.00	51.00
1980	7	31.71	4502.29	1331.00	68.00
1979	8	44.89	4506.11	1592.00	65.00
1978	9	22.44	4043.56	1558.00	102.00
1977	10	61.14	4043.86	2152.00	113.00
1976	11	0.00	3613.00	1892.00	122.00
1975	12	0.00	3088.00	1745.00	130.00
1974	13	7.20	2728.80	2229.00	93.00
1973	14	81.76	4008.24	1402.00	107.00
1972	15	59.71	3726.29	1017.00	90.00
1971	16	24.41	3179.59	779.00	159.00
1970	17	24.01	3276.99	690.00	152.00
1969	18	34.15	2930.88	1059.84	104.13
1968	19	30.63	2629.20	950.75	93.41
1967	20	26.07	2237.38	809.06	79.49
1966	21	30.52	2619.27	947.16	93.06
1965	22	29.65	2544.73	920.21	90.41
1964	23	29.15	2502.14	904.81	88.90
1963	24	31.26	2683.15	970.26	95.33
1962	25	30.84	2646.95	957.17	94.04
1961	26	27.73	2380.05	860.66	84.56
1960	27	34.78	2984.83	1079.35	106.05
1959	28	31.62	2713.67	981.30	96.41
1958	29	25.20	2162.85	782.11	76.84
1957	30	29.48	2530.54	915.07	89.91
1956	31	26.86	2305.52	833.70	81.91
1955	32	26.58	2281.39	824.98	81.05
1954	33	25.10	2154.33	779.03	76.54
1953	34	25.20	2162.85	782.11	76.84
1952	35	29.98	2573.13	930.47	91.42
1951	36	29.20	2506.40	906.35	89.05
1950	37	29.81	2558.93	925.34	90.92
1949	38	25.55	2192.66	792.89	77.90
1948	39	31.38	2693.09	973.85	95.68
1947	40	31.80	2729.29	986.94	96.97

Distribution and Historic Volumes: British Columbia

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.822	0.178	0.000
Hardwoods	0.017	0.983	0.000

Historic volumes of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool

Year of simulation	Age (years)	Wood harvested ('000 m^3)			
		Hardwood lumber	Softwood lumber	Pulpwood	Fuelwood
1986	1	281.00	58 022.03	19 199.97	0.00
1985	2	281.00	58 358.38	18 228.62	0.00
1984	3	281.00	58 034.46	16 240.54	0.00
1983	4	281.00	53 916.83	17 245.17	0.00
1982	5	221.00	41 442.84	14 567.16	0.00
1981	6	233.00	45 931.42	14 615.58	0.00
1980	7	258.00	57 066.10	17 329.90	0.00
1979	8	227.00	59 255.40	16 712.60	0.00
1978	9	127.00	58 617.92	16 419.08	0.00
1977	10	136.00	55 216.39	14 618.61	0.00
1976	11	207.00	53 215.68	16 098.32	0.00
1975	12	516.00	37 464.05	12 097.95	0.00
1974	13	561.00	43 587.06	15 937.94	0.00
1973	14	577.00	53 410.24	16 149.76	0.00
1972	15	306.00	42 299.02	13 846.98	0.00
1971	16	293.00	42 915.37	13 341.63	0.00
1970	17	327.00	41 993.40	12 406.60	0.00
1969	18	370.78	40 276.88	12 877.34	0.00
1968	19	333.98	36 278.92	11 599.11	0.00
1967	20	308.51	33 512.77	10 714.71	0.00
1966	21	314.36	34 147.87	10 917.70	0.00
1965	22	300.76	32 670.74	10 445.50	0.00
1964	23	297.13	32 276.44	10 319.43	0.00
1963	24	289.05	31 398.28	10 038.67	0.00
1962	25	263.45	28 617.84	9 149.70	0.00
1961	26	228.96	24 871.21	7 951.83	0.00
1960	27	235.38	25 568.76	8 174.85	0.00
1959	28	230.32	25 018.70	7 998.98	0.00
1958	29	195.95	21 284.85	6 805.20	0.00
1957	30	204.54	22 218.69	7 103.77	0.00
1956	31	217.75	23 652.93	7 562.32	0.00
1955	32	212.03	23 032.13	7 363.84	0.00
1954	33	195.42	21 227.67	6 786.92	0.00
1953	34	189.39	20 573.00	6 577.61	0.00
1952	35	178.54	19 394.61	6 200.85	0.00
1951	36	169.15	18 374.23	5 874.62	0.00
1950	37	163.32	17 740.64	5 672.04	0.00
1949	38	144.41	15 687.10	5 015.48	0.00
1948	39	153.59	16 684.15	5 334.26	0.00
1947	40	149.71	16 262.00	5 199.29	0.00

Distribution and Historic Volumes: Yukon Territory

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.80	0.20	0.00
Hardwoods	0.00	1.00	0.00

Historic volumes (1947–1986) of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool, have a value of zero for Yukon.

Distribution and Historic Volumes: Northwest Territories

Proportional distribution of harvest to saw lumber, pulpwood, and fuelwood in the carbon budget framework

Harvest	Saw lumber	Pulpwood	Fuelwood
Softwoods	0.80	0.20	0.00
Hardwoods	0.00	1.00	0.00

Historic volumes (1947–1986) of wood harvested, used to set up the initial conditions for the various product pools and the landfill pool, have a value of zero for the Northwest Territories.

APPENDIX 7
AREA ESTIMATES FOR FIVE DISTURBANCE TYPES, BY ADMINISTRATIVE PROVINCE AND ECOCLIMATIC PROVINCE

Area estimates: wildfire

Ecoclimatic province	Administrative province (ha)												Total area	Percentage of total area
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories		
Arctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic	17 472	0	0	0	273 578	676	2 456	21 532	0	0	14 782	229 554	560 050	22.4
Boreal West	0	0	0	0	0	0	391 766	668 596	236 536	9 506	1 054	162 092	1 469 550	58.9
Boreal East	5 984	0	0	176	97 150	187 091	0	0	0	0	0	0	290 401	11.6
Cool Temperate	0	0	0	4 865	74	38	0	0	0	0	0	0	4 977	0.2
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grassland	0	0	0	0	0	0	8 374	0	632	0	0	0	9 006	0.4
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	2 998	0	2 998	0.1
Cordilleran	0	0	0	0	0	0	0	0	26 118	80 306	42 097	1 494	150 015	6.0
Interior Cordilleran	0	0	0	0	0	0	0	0	0	6 996	0	0	6 996	0.3
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	2 006	0	0	2 006	0.1
Total	23 456	0	0	5 041	370 802	187 805	402 596	690 128	263 286	98 814	60 931	393 140	2 495 999	
Percentage of total area	0.9	0.0	0.0	0.2	14.9	7.5	16.1	27.6	10.5	4.0	2.4	15.8		

Area estimates: insects

Ecoclimatic province	Administrative province (ha)												Total area	Percentage of total area
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories		
Arctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal West	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal East	47 790	46 774	0	7 064	116 451	97 076	0	0	0	0	0	0	315 155	81.3
Cool Temperate	0	2 462	0	10 595	29 113	1 578	0	0	0	0	0	0	43 748	11.3
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Cordilleran	0	0	0	0	0	0	0	0	503	13 887	0	0	14 390	3.7
Interior Cordilleran	0	0	0	0	0	0	0	0	0	14 281	0	0	14 281	3.7
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Total	47 790	49 236	0	17 659	145 564	98 654	0	0	503	28 168	0	0	387 574	
Percentage of total area	12.3	12.7	0.0	4.6	37.6	25.5	0.0	0.0	0.1	7.3	0.0	0.0		

Area estimates: cut and burn

Ecoclimatic province	Administrative province (ha)												Total area	Percentage of total area
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories		
Arctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal West	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal East	0	0	0	0	0	4 050	0	0	0	0	0	0	4 050	6.9
Cool Temperate	0	0	0	0	0	258	0	0	0	0	0	0	258	0.4
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Cordilleran	0	0	0	0	0	0	0	0	0	26 353	0	0	26 353	45.2
Interior Cordilleran	0	0	0	0	0	0	0	0	0	15 884	0	0	15 884	27.2
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	11 754	0	0	11 754	20.2
Total	0	0	0	0	0	4 308	0	0	0	53 991	0	0	58 299	
Percentage of total area	0.0	0.0	0.0	0.0	0.0	7.4	0.0	0.0	0.0	92.6	0.0	0.0		

Area estimates: clear-cut

Ecoclimatic province	Administrative province (ha)												Total area	Percentage of total area
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories		
Arctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal West	0	0	0	0	0	0	15 846	19 963	16 913	0	3	960	53 685	6.9
Boreal East	16 400	13 153	0	16 390	205 828	170 012	0	0	0	0	0	0	421 783	54.4
Cool Temperate	0	15 647	3 200	66 330	36 323	10 852	0	0	0	0	0	0	132 352	17.1
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grassland	0	0	0	0	0	0	54	0	0	0	0	0	54	0.0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Cordilleran	0	0	0	0	0	0	0	0	16 913	73 465	124	30	90 532	11.7
Interior Cordilleran	0	0	0	0	0	0	0	0	0	44 281	0	0	44 281	5.7
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	32 766	8	0	32 774	4.2
Total	16 400	28 800	3 200	82 720	242 151	180 864	15 900	19 963	33 826	150 512	135	990	775 461	
Percentage of total area	2.1	3.7	0.4	10.7	31.2	23.3	2.1	2.6	4.4	19.4	0.0	0.1		

Area estimates: partial cut

Ecoclimatic province	Administrative province (ha)												Total area	Percentage of total area
	Newfoundland	Nova Scotia	Prince Edward Island	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Yukon	Northwest Territories		
Arctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal West	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Boreal East	0	447	0	862	9 131	30 843	0	0	0	0	0	0	41 283	46.2
Cool Temperate	0	531	0	3 488	14 899	1 969	0	0	0	0	0	0	20 887	23.4
Moderate Temperate	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Subarctic Cordilleran	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Cordilleran	0	0	0	0	0	0	0	0	0	7 032	0	0	7 032	7.9
Interior Cordilleran	0	0	0	0	0	0	0	0	0	18 225	0	0	18 225	20.4
Pacific Cordilleran	0	0	0	0	0	0	0	0	0	1 968	0	0	1 968	2.2
Total	0	978	0	4 350	24 030	32 812	0	0	0	27 225	0	0	89 395	
Percentage of total area	0.0	1.1	0.0	4.9	26.9	36.7	0.0	0.0	0.0	30.5	0.0	0.0		