Canada's Model Forest Program

# Carbon Budget Accounting at the Forest Management Unit Level:

## An Overview of Issues and Methods

*July 2000*

MODEL FOREST NETWORK

RÉSEAU DE FORÊTS MODÈLES

### The Canadian Forest Service:

Mission: "To promote the sustainable development of Canada's forests and competitiveness of the Canadian forest sector for the well-being of present and future generations of Canadians".

Canada has taken the lead in researching ways to sustain and enhance our forests. The Government of Canada, through the Canadian Forest Service, initiated the Model Forest Network in 1992. It introduced this system of 11 Canadian and a number of international research sites "dedicated to building partnerships locally, nationally, and internationally to generate new ideas and on-the-ground tools for sustainable forest management". This process has brought together hundreds of partners including academia, industry, government, communities, aboriginal peoples, the public, and other stakeholders.

The Canadian Forest Service of Natural Resources Canada is also a principal partner in each of the eleven model forest organizations and provides primary funding and administrative support to Canada's Model Forest Program.

Web site: **www.NRCan.gc.ca**

### What is a Model Forest?

A model forest is a place where the best sustainable forest management practices are developed, tested and shared across the country. Each model forest is run by a not-for-profit organization, and, except for a small administrative staff, all those involved in the model forest not only donate their time and expertise, but usually bring additional financial support.

At the heart of each model forest is a group of partners having different perspectives on the social, economic and environmental dynamics within their forest – perspectives that are necessary to make more informed and fair decisions about how to manage the forest. The real "model" in these forests is the way the different partners – logging companies, Aboriginal communities, maple syrup producers, woodlot owners, parks, environmentalists, universities, government agencies, recreational groups, community associations, hunters, trappers - have integrated their own interests into their common goal of developing approaches to sustainable forest management that do not sacrifice one interest for another.

Although the model forest organization itself does not have jurisdiction over the land it uses as a testing ground, those who do have jurisdiction are participants. By being involved from the outset in developing new, on-the-ground approaches and solutions for sustainable forest management, those with land management responsibilities are increasingly adopting many of the model forest suggestions.

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# Carbon Budget Accounting at the Forest Management Unit Level:

## An Overview of Issues and Methods

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# Summary

This report has been prepared in response to an identified need to provide guidance to forest managers seeking to report on a carbon budget at the scale of the forest management unit (FMU). This effort has been supported by the Local Level Indicators Strategic Advisory Committee of the Canadian Model Forest Network.

A brief overview of work on carbon budgeting across the Model Forest Network shows that only at the Foothills Model Forest has there been any comprehensive effort made to report on carbon fluxes in the forest. Many model forests have expressed the view that the issue is best dealt with at a provincial or national level, rather than at a FMU level. This report takes a different view and argues that preliminary carbon budgeting at the FMU level will, in many cases, not present any insurmountable challenges and, moreover, if carbon accounting is to actually influence management decisions then it must be brought down to the forest management unit scale.

Carbon is present in living biomass, dead or decomposing organic matter, soil organic matter, mineral soils and forest products. These carbon "pools" are not stable and they change in different ways, with carbon being added to each pool through a variety of natural and anthropogenic causes and leaving the pool at varying rates either to enter another pool or to be re-emitted into the atmosphere.

Carbon budgeting can be broken down into three distinct tasks:

- Obtaining a baseline measurement of the amount of carbon in a particular forest at a given time;
- Measuring the change to that stock over time; and
- Evaluating the likely impact of various management activities on future changes to the carbon budget.

Each of these is discussed in turn, describing the information that is needed by forest managers in order to apply these steps in their particular forest management unit. These methods can be used in three different ways to track changes over time to the carbon stocks: by comparing successive baseline measurements; by tracking changes since one baseline measurement; or by measuring changes on their own, without reference to a baseline. The advantages and disadvantages of each method are discussed briefly.

This report focuses on how to use existing inventories to record carbon stocks and fluxes. The use of direct measurement and remote sensing have an important potential role to play in carbon budgeting, but are not discussed in this report because at the present time their successful application to carbon budget estimation is still dependent upon good baseline estimates derived from inventory-based carbon budget assessments.

The challenge of recording changes to the forest products pool is dealt with separately from the challenge of recording changes in the forest.

The Canadian Forest Service has developed a number of tools to assist in carbon budget modelling, including a model for the Canadian forest sector and one specifically for the forest products sector. These models are briefly described, along with initiatives to apply these models at the level of a forest management unit.

The report concludes with a listing of some activities that could help to store carbon in forests.

# Key Messages and Recommendations

## To forest managers:

1. Measuring carbon and carbon fluxes at the forest management unit level is not technically difficult and can be done with data that is readily available to most forest managers.

2. Although initial measurements are likely to be somewhat imprecise and may not include all carbon pools, that in no way invalidates their usefulness to forest managers who wish to incorporate an awareness of climate change issues in their assessments, plans, monitoring and reporting.

3. Forest managers should report on the best available information rather than waiting for "perfect" information to become available. Reporting now is the best way to generate the commitment to refine and improve upon initial estimates.

4. Several reports, available from the Canadian Forest Service's Northern Forest Centre, provide enough information to get started. "The carbon budget of the Canadian forest sector" (Kurz *et al* 1992, Information Report NOR-X-326) provides an excellent overview of the CFS Carbon Budget Model, while "A soil profile and organic carbon data base for Canadian forest and tundra mineral soils (Siltanen *et al* 1997) provides the necessary data on regional soil profiles. Other reports include, "A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector" (Kurz and Apps 1999) and "Carbon budget of the Canadian forest product sector" (Apps *et al* 1999). Carbon conversion factors are included in Figure 1 above (p.5). The other information needed to get started – volume of timber, growth yield curves, information about logging and natural disturbances – must be obtained locally.

5. There are several forest management measures that can augment the ability of forests to store carbon, and that are consistent with sustainable forest management. Long-term approaches that increase the overall storage of carbon (measured as tonnes/hectare/year, averaged out over a century or more) are more valuable than approaches that focus primarily on increasing the rate of short-term sequestration.

## To the Model Forest Network:

6. The Model Forest Network is well situated to play an important role in promoting the development of a universal carbon budget model that could be easily used with commonly available information by any forest manager. The Canadian Forest Service already has most of the elements needed to create a credible, easy-to-use universal model and the support of and collaboration from the Model Forest Network could help to make this a priority.

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# 1. Introduction

## 1.1 Context

It is now generally agreed that global climate is being affected by human activities that result from the emission of certain greenhouse gases into the atmosphere. There are three main ways that forests and forest management are relevant to climate change issues:

a) The forest industry and its related infrastructure produce significant emissions of greenhouse gases in its upstream activities (site preparation, silviculture, logging, transportation to mills), manufacturing processes, and downstream activities (transportation to markets, as well as emissions resulting from decomposition and recycling). Efficiencies that result in reduced emissions of greenhouse gases would help to mitigate climate change.

b) Forests are significant reservoirs of carbon. Compounds of carbon such as carbon dioxide ($CO_2$), methane ($CH_4$), and certain organic molecules are the major greenhouse gases. When carbon is stored in forests (in living biomass, dead biomass or soils) or in forest products it is not in the atmosphere. Loss of forests on a global scale is a significant contributing factor in climate change. On the other hand, the possibility of expanding carbon storage in forests (i.e., creating "sinks") has been identified as a potential short-term measure to mitigate climate change.

c) Forests are vulnerable to climate change and are expected to react in a variety of ways that are not yet reliably predictable. A longer growing season may result in enhanced growth which may be partially or fully offset by increased respiration. Shifting climatic zones may enable forests to become established in regions currently unforested (although in many such regions the soils may not be present to support forests). On the other hand, shifting climatic zones may increase trends towards forest loss or even desertification in some regions of the world and predicted impacts such as drought and extreme weather events may increase the frequency and scale of disturbances such as fire, insects and storm damage.

This report is mainly concerned with the second of these three points, without in any way seeking to diminish the importance of the other two considerations.

The importance of the Canadian forest sector "carbon budget" is recognized in the Criteria and Indicators of Sustainable Forest Management framework that was developed for the Canadian Council of Forest Ministers. Criterion Four acknowledges the importance of forest ecosystem contributions to global ecological cycles, and nine of the indicators deal specifically with information needed to determine a forest sector carbon budget.

There are several distinct reasons why it is important to measure and report on forest sector carbon budgets. Carbon budgets record whether and how forests are contributing to or mitigating climate change. They promote better understanding of the varied and complex ways that forests respond to and affect climate. Finally, and perhaps most importantly, they allow forest managers to include carbon storage as one of the factors to be considered when evaluating different management options.

For this latter potential to be realized, however, it is crucial that carbon accounting be brought down from global and national scales to the scale most relevant to a particular forest manager; namely a forest management unit. This has not yet been done in a systematic and universally accepted way, however, and there is therefore an opportunity for the Canadian Model Forest Network to demonstrate leadership in this regard.

## 1.2 Purpose

The purpose of this report is to provide an overview of the tools that are available or in development to enable forest managers to track changes in carbon storage in forests at the local level. It also reviews the applicability of the Canadian Forest Service's Carbon Budget Model at the forest management unit level, enabling forest managers to assess how management decisions can be expected to impact on carbon storage at the local level.

# 2. Key Concepts

The definitions and clarifications in this section are intended to introduce a few key concepts, especially in areas where there is frequent confusion. These are not intended to be rigorous technical definitions.

**Carbon, $CO_2$, and $CH_4$:** When carbon is measured in trees or soils it is usually described in units of carbon. When organic matter carbon decomposes and enters the atmosphere it does so primarily as carbon dioxide which is why greenhouse gas emissions are measured as tonnes of $CO_2$. A tonne of carbon, if allowed to decompose and return to the atmosphere, produces 3.667 tonnes of $CO_2$. Likewise, creating a new reservoir of a tonne of carbon is the equivalent to a 3.667 tonne reduction in $CO_2$. Under anerobic (oxygen depleted) conditions such as those found in low-land or peat-forming forests, methane ($CH_4$) is produced and can make a large contribution to the net greenhouse gas flux. Methane is a more active greenhouse gas than $CO_2$ (from an atmospheric impact point of view, 1 tonne of $CH_4$ is equivalent to approximately 20 tonnes of $CO_2$).

**Forest carbon pools:** There is carbon in living biomass, dead or decomposing organic matter, soil organic matter, mineral soils and forest products. These categories often get lumped together into a few clusters but different accounting methods do this differently. Some distinguish between above-ground and below-ground carbon while others distinguish between biomass and soil carbon. There does not seem to be consistency among scientists about precisely when decaying woody material changes from biomass to soil. This probably doesn't matter much for a forest manager but it is worth noting that different carbon budget models use different rules to determine how carbon from the biomass pool enters the soils pool.

Different levels of detail in any carbon accounting system are briefly discussed below.

**Net Primary Production:** The total amount of photosynthesis minus the total amount of plant respiration. Photosynthesis, which sequesters carbon, tends to be highest during the day and during the summer but some of this sequestered carbon is re-emitted through plant respiration at night and during winter.

**Net Ecosystem Production:** Net Primary Production minus losses due to decomposition as leaf litter, dead trees, roots and fallen branches decay, and as the tree itself succumbs to rot.

**Net Biome Production:** Net Ecosystem Production minus losses due to disturbances including natural disturbances such as fire, insects, disease and windthrow as well as anthropogenic disturbances such as logging and deforestation.

**Forest Sector Accounting:** Achieving truly full carbon accounting for the forest sector is perhaps an abstract ideal. Full sector accounting would add to Net Biome Production, including the carbon added to the forest products carbon pool as well as any credit from the use of biomass energy to displace fossil fuels. Subtracted from that total would be the rate of decomposition of forest products as well as energy inputs throughout the forest management cycle (see item (a) in 1.1 above).

In general, an adequate carbon budget for a particular forest area will include Net Biome Production at a minimum. Usually some effort is made to include elements of a forest sector accounting system but in this case it is important to take a balanced approach to accounting for sources of carbon as well as sinks.

It is often assumed that the main purpose of carbon accounting is to support the objectives of international agreements on climate change and their reporting requirements. This need not necessarily be the case but to avoid confusion it is important to distinguish between the very different requirements of the two major legal instruments pertaining to climate change.

**Framework Convention on Climate Change:** Negotiations on the Framework Convention were completed at the Earth Summit in 1992 and it has since been ratified by enough countries (including Canada) that it has entered into effect. Signatory countries commit to promote the conservation and enhancement of sinks and reservoirs, and to develop and publish national inventories of greenhouse gas emissions including anthropogenic activities related to sinks. The reporting requirements are mandatory, following somewhat flexible guidelines (IPCC 1997) with respect to land-use change and forestry. Notably, there are no legally binding emissions reduction targets in the Framework Convention.

**The Kyoto Protocol:** This is a subsidiary agreement to the Framework Convention agreed to in 1997 and signed but not yet ratified by Canada and not yet in force. It sets specific target levels that certain countries agree to conform to in their greenhouse gas emissions. Countries must include in their inventories any changes in carbon stocks between 2008 and 2012 due to afforestation, reforestation or deforestation activities since 1990 (in other words, only a very small area relative to the entire forest). There is also a provision that other land management activities may be included in national inventories. The rules for such other activities, as well as the precise definitions of afforestation, reforestation and deforestation, will not be determined until November 2000 at the earliest. Until these negotiations are completed there is considerable uncertainty about what forest activities are included in the Kyoto Protocol[1]. It is important to note that the accounting methods discussed in this report are not designed to address the measurement requirements under the Kyoto Protocol.

What does this mean for forest managers? Neither international agreement relates precisely to what is described in this report. The Framework Convention requires only that reporting take place on a national scale, while the Kyoto Protocol still has so many unresolved details that it is not possible to say what the accounting rules must include. Nevertheless, there is a strong case to be made that there is a need for local level implementation of the type of carbon accounting discussed in this report. If Canada is to promote the conservation and enhancement of forest sinks and reservoirs, actual on-the-ground activities in support of this objective must for the most part be carried out by local managers. They therefore need good information that will tell them what impact their management activities are having. An adequate carbon budget is an essential tool in this regard.

One final clarification is important; namely, the difference between sinks and reservoirs.

**Sinks and reservoirs:** A sink is an activity that removes (or "sequesters") carbon from the atmosphere and is the opposite of a "source." A reservoir, on the other hand, is the actual "pool" of carbon itself, safely stored in a form that keeps it out of the atmosphere for a short or long period of time. The difference between these two terms is crucial. A young growing forest, for instance, is a good carbon sink since it sequesters carbon at a high rate. An old forest, however, will generally be a better carbon reservoir since it stores a greater volume of carbon and it provides this service even though its growth has levelled off. So an old forest may be a good forest reservoir although a poor forest sink (or even a slight source). The "sinks" potential of a forest can be determined by measuring the extent to which more carbon is flowing into it than flowing out (IPCC 2000). The reservoir potential, on the other hand, can be measured by determining the tonnes of carbon per hectare per year, averaged out over a time scale at least as long as one full rotation period. The carbon accounting processes described in this report can be used for both calculations. It is worth noting in passing that the Kyoto Protocol recognizes the role of forest sinks while the Framework Convention places more emphasis on forests as carbon reservoirs. As policy instruments then, the two agreements have the potential to work at cross purposes. If forest management is to adequately consider the long-term scales (>100 years) appropriate to forest ecosystem cycles as well as in mitigating climate change, however, the role of forests as long-term carbon reservoirs is considerably more significant than their relatively short-term role as sinks.

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[1] For example, the net impact of reforestation and deforestation in Canada, based on "business as usual" activities, is estimated to range between being a 21 Mt/year source of $CO_2$ and being a 10 Mt/year sink (Forest Sector Table 1998). This huge range is based entirely upon differing views about what might be included in the Kyoto Protocol.

# 3. Tasks

In essence, there are three tasks involved in carbon budgeting:

1. Obtaining a baseline measurement of the amount of carbon in the local area at a given time.

2. Measuring changes to that stock over time.

3. Evaluating the likely impact of various management activities on the forest's ability to serve as a carbon reservoir and incorporate that knowledge into the decision-making process.

Each of these tasks are considered respectively in Sections 6, 7 and 8 of this report.

# 4. Methods

There is currently a tremendous amount and diversity of scientific activity being carried out related to forests and carbon accounting, with a variety of methods used for measurement, modelling and accounting purposes. These methods also operate at widely different scales, an important factor when considering carbon budget accounting for forest management units.

**Direct measurement:** This is the finest level of detail and includes research into plant photosynthesis, decomposition rates, soil profiles, etc. The data from such small-scale studies, however, is difficult to "scale up" to estimate carbon throughout a forest management unit and is therefore not discussed in this report. Direct measurement is aimed more at quantifying carbon sinks and how they are influenced by environmental conditions than it is at estimating carbon reservoirs.

**Inventory bookkeeping:** This refers to the use of forest inventories and other information with sinks (Net Ecosystem Production, carbon in forest products) tallied on one side of the ledger and sources (disturbances, logging, forest product decay, other emissions) on the other side. This is the method that is generally used in developing forest carbon budgets at scales larger than the stand level. Of course, its accuracy depends on the completeness and accuracy of the information. As well, although there are soil profiles for much of Canada that include estimates of carbon content, other methods are needed to estimate the impacts that disturbances and forest management are likely to have on soil carbon pools.

**Remote sensing:** There are increasing efforts to employ remote sensing to provide global estimates of carbon fluxes in forests. Remote sensing can provide for greater consistency when trying to aggregate data from several inventories and can fill in gaps where inventory information is unavailable. However, remote sensing technologies have not yet been validated to provide an acceptable level of accuracy. As well, remote sensing is not an effective tool for measuring soil carbon. In general, remote sensing is finding its most valuable applications in helping to carry out global assessments of how climate change might be having an impact on forests around the world by tracking major disturbances, changes in the growing season, and Net Primary Productivity. Potential future applications also include using remote sensing data to scale process models built from direct measurement of carbon fluxes obtained from relatively few individual sites.

This report is based on the notion that the preferred method for carbon accounting at the forest management district level is likely to be through inventory bookkeeping methods with direct measurements to refine the accuracy of assumptions and remote sensing to help fill in gaps. Forest managers that do not have adequate timber inventories will not be able to easily obtain good baseline measurements but that doesn't necessarily prevent them from recording carbon fluxes.

There are more measurement methods than covered by this report. In particular, mention should be made of direct flux measurements through the use of flux towers, chambers, and aircraft which are used for model verification purposes. Chapter 2 of the IPCC's Special Report on Land Use, Land-use Change, and Forestry provides a concise summary of the various methods and their limitations.

# 5. Model Forests and Carbon Accounting

A quick scan across the Model Forest Network suggests that there is relatively little activity on carbon budgeting. The following are a few points that have been gleaned from the research carried out in compiling a reference document summarizing model forest accomplishments in using local level indicators, and from other sources.

**Foothills Model Forest** have no doubt done the most since they have actually produced a Carbon Budget Model for their forest. The results are discussed briefly in Section 8 below. The model used was developed and run by the Canadian Forest Service. This research project was performed to demonstrate the feasibility of performing such analyses at an operational scale. However, the model is not yet user-friendly enough that it could easily be used by forest managers on their own.

**Fundy Model Forest** has six indicators in the "Contributions to the Global Carbon Budget" section of the Model Forest Network's general matrix of indicators. However, that Model Forest believes that these indicators are non-functional at the local level and best left to provincial and federal agencies. Fundy had proposed a collaboration with Foothills Model Forest to test and refine the national assumptions relating to soil carbon but it did not receive sufficient support to be implemented. The problem seemed to be that the proposed project worked at the "micro" scale while the carbon budget modelling team at CFS is more concerned about the "macro" scale.

**Western Newfoundland Model Forest** has two indicators in the "Contributions to the Global Carbon Budget" section of the Model Forest Network's general matrix of indicators. However, it has not gathered data on these indicators. It is involved in a proposal to explore the possibility of gathering inventory information using a grid sampling method in such a way as to meet provincial reporting requirements and, at the same time, gather information usable at the FMU scale. It has also indicated an interest in learning the results of a national study being carried out by CFS which will assess the potential of remote sensing as a tool to measure biomass. Both of these studies will require considerable testing and evaluation before producing results that could be applied at the local level.

**Lake Abitibi Model Forest** has listed three indicators in the "Contributions to the Global Carbon Budget" section of the Model Forest Network's general matrix of indicators but has not yet completed its first data gathering exercise.

**Eastern Ontario Model Forest** is the first (and only) model forest to report on the current state of its forest across a broad range of indicators but its *State of the Forest Report* does not include a measure of the amount of carbon in the forest.

No other model forest has listed indicators under the category "Contributions to Global Carbon Budget."

# 6. Obtaining Baseline Measurements

## 6.1 Carbon in living biomass

This measurement is easily obtained provided that the amount of standing timber on the forest at a given time is known from a current forest inventory. The volume of timber needs to be converted to a total biomass volume and then converted into a mass of carbon or $CO_2$. The conversion factors provided in Figure 1 are based on those reported by the Intergovernmental Panel on Climate Change's Greenhouse Gas Inventory Guidelines *Reference Manual* and modified by Environment Canada using Canadian data. Even with these modifications, the conversion factors are only general approximations or averages. There may well be more accurate conversion tables, keyed to specific species, age classes and soil types, all of which can be expected to influence the ratio of below-ground to above-ground biomass. Nevertheless, these figures can provide a reasonable starting point and they are considered acceptable for national and international reporting requirements.

**Figure 1: Conversion factors**

1. To modify inside bolewood volume to include non-merchantable volume such as bark, tops and branches:
   **Multiply bole volume by 1.454**
2. To estimate below-ground volume:
   **Multiply bole volume by .396**
3. To obtain total wood volume:
   **Add 1 and 2**
4. To convert wood volume ($m^3$) to tonnes of dry matter biomass:
   **Multiply wood volume by .43**
5. To convert dry matter biomass to carbon:
   **Multiply dry matter biomass by .5**
6. To convert carbon to $CO_2$ equivalent:
   **Multiply carbon by 3.6667**

## 6.2 Soil carbon

There is data on soil carbon for sites across Canada in a study entitled *A soil profile and organic carbon data base for Canadian forest and tundra mineral soils* (Siltanen *et al* 1997). Information is based on profiles collected from 1462 sites across Canada. The results are generalized in Table 1 below, reproduced from that report. The site locations are shown on an accompanying map and the report comes with a disk that provides detailed information on each of these sites.

It's important to note that these soil profiles do not necessarily accurately predict the amount of carbon present on an actual site. They represent, however, the best available information for Canada as a whole and are generally considered to be of sufficient accuracy for carbon budgeting, modelling and reporting, although they could obviously be improved upon by using better local data or taking additional direct measurements in a particular forest management unit.

Many Canadian forest operations take place in imperfectly drained (low-land) forests where peat (or deep organic) soils prevail. Under these conditions, changes in methane ($CH_4$) production as well as $CO_2$ production contribute to the net greenhouse gas balance. At present, the Canadian Forest Service does not systematically include this methane, or peatland dynamics, in the carbon budget although CFS currently has an active program to include peatland processes (in low-land forests) in the carbon budget model.

**Table 1:** Mean organic carbon content (kg $m^{-2}$) by ecoclimatic province

| Ecoclimatic province | Mineral horizons[a] | Organic horizons[b] |
|---|---|---|
| Arctic | 8.4 ± 1.0 (76)[c] | 3.4 ± 0.6 (25) |
| Subarctic | 7.6 ± 0.5 (154) | 3.9 ± 0.2 (150) |
| Boreal West | 5.4 ± 0.2 (374) | 2.7 ± 0.1 (370) |
| Boreal East | 7.3 ± 0.3 (286) | 3.8 ± 0.2 (286) |
| Cool Temperate | 10.5 ± 0.8 (86) | 2.0 ± 0.3 (86) |
| Moderate Temperate | 7.0 ± 0.8 (3) | 1.6 ± 0.4 (3) |
| Grassland | 9.3 ± 1.6 (7) | 3.0 ± 0.7 (7) |
| Subarctic Cordilleran | 13.9 ± 1.9 (16) | 2.2 ± 0.3 (16) |
| Cordilleran | 8.5 ± 0.3 (326) | 2.7 ± 0.1 (321) |
| Interior Cordilleran | 7.5 ± 0.7 (67) | 1.8 ± 0.2 (67) |
| Pacific Cordilleran | 23.2 ± 1.9 (67) | 4.6 ± 0.4 (67) |

[a] All horizons below the mineral surface.
[b] All horizons above the mineral surface. Not all profiles in the data set have data for organic horizons above the mineral surface. This summary includes only those profiles that have measured or estimated organic horizon data. This can result in a different sample size than that for the mineral horizon summary.
[c] Mean ± standard error of the mean (sample size).

(Source: Siltanen *et al* 1997)

# 7. Estimating Carbon Fluxes

There are three ways to measure carbon fluxes in a particular forest area based on changes in forest ecosystem pools:

1) compare successive inventories;
2) use one inventory as a baseline and measure changes from that baseline by totalling additions and removals; or
3) measure additions and removals on their own without reference to a baseline.

All three are briefly discussed below. As mentioned previously, direct flux measurement methods – using towers, chambers and aircraft – are used in verifying the models and their estimates and are not covered in this report.

## 7.1 Comparing successive baseline measurements

Section 6 above already explains how to use forest inventories to estimate the amount of carbon on a site. This estimate can easily be carried out on two or more successive inventories to show trends over time.

**Advantages:** Obviously, this is the easiest method; if the forest area has a regularly updated timber inventory, it is simply a matter of applying the conversion factors to two or more inventories. Another advantage is that historical records can be used to construct trends going back in time.

**Disadvantages:** If different methodologies are used in successive inventories, this will add error to the calculation. This error could be significant if the net changes of carbon in the inventories are small compared to the amount of carbon in the inventories. This method does not show what the main factors are in affecting carbon stocks in a particular area since all of the combined losses from logging, natural disturbances and deforestation will be rolled together. As well, this method does not, by itself, provide estimates of changes in soil carbon stocks. Such estimates would have to be separately measured or estimated using models.

## 7.2 Baseline plus estimated stock changes

In this method, one inventory is used as a baseline and then all deviations from it are recorded.

**Additions:** The additions to above-ground carbon stocks is the above-ground Net Ecosystem Productivity; this information is typically contained in growth yield curves and summarized in mean annual increment estimates. The conversion figures in Figure 1 should be used to derive carbon figures. Growth yield curves often do not extend back to cover the early years of stand development. This missing information can be filled in by drawing an exponential curve from zero to the first data point. Even a straight line will do; any inaccuracies will be quite small when compared with the overall carbon in the forest.

**Withdrawals:** Forest management records can usually supply the following, all of which are needed:

- volume of timber lost to fire, insects, disease and other natural disturbances (other than normal stand breakup, which is captured in the growth yield curves);
- volume of timber logged; and
- volume estimates of losses due to deforestation (road building, land-use conversion, hydro and other developments, etc). These figures may already be captured in the volume logged, in which case they need not be counted here although the area deforested will lessen the future productivity of the landbase.

All of the figures above will usually be available as a measure of volume of timber. The conversion factors in Figure 1 should be used to derive estimates of weight of carbon or $CO_2$.

These calculations will allow for a reasonably accurate assessment of fluxes in the standing biomass pool. Measuring changes in soil carbon pools is a bit trickier. See Section 8 for a brief overview of the Carbon Budget Model developed by the Canadian Forest Service. As well, see Section 9 for a discussion about tracking the flow of carbon through the forest products pool.

**Advantages:** This method is reasonably accurate and is basically the method followed in most carbon budget models. The information is usually available.

**Disadvantages:** The CFS Carbon Budget Model has not yet been made generally available for use by forest managers and, although the assumptions used by the model of how carbon enters and flows through the soil carbon pool are available, actually carrying out the calculations would be extremely labourious with the present research-oriented version.

### 7.3 Measuring flux alone (Net Biome Production)

It is also possible to carry out carbon accounting without obtaining a baseline measurement, simply by recording the net effects of additions and withdrawals and report that as the change in carbon storage.

**Advantages:** This method may be particularly attractive in situations where the basic forest inventory has significant gaps in it since it does not presume to offer an absolute measure of carbon (which would likely be highly inaccurate) but only measures changes to carbon stocks over specified intervals.

**Disadvantages:** Changes in carbon stocks can only be reported in absolute terms (as tonnes of carbon lost or gained) and not as a percentage of the entire carbon pool. This may or may not be a significant disadvantage.

### 7.4 Summary

*The section above has described, in the simplest terms possible, the "heart" of any carbon budgeting system.*

In general, most forest managers with an adequate inventory would most conveniently use the baseline plus flux method since this is most consistent with practises followed elsewhere. However, measuring flux alone may be an attractive option in forests lacking an adequate timber inventory since this would meet the basic requirements of carbon accounting. Simply comparing baselines can be used as a "back of the envelope" initial calculation or, if adequate inventory information is available, can be used to plot rough historical trends.

*In conclusion, there is nothing particularly technically complex or prohibitively expensive in carbon accounting at the forest management unit level.*

Obviously, any accounting system will only be as accurate as the accuracy of the information going into it. Even a FMU with up-to-date information is likely to have a number of gaps, errors and uncertainties associated with the data. However, is it better to wait until perfect information is available, or to wade in and obtain, at relatively little cost and effort, the best estimates that can be derived from currently available information and then to use that initial work to guide efforts to improve upon and refine the estimates?

## 8. Carbon in Forest Products

Forest management actions can have a significant impact on the amount of carbon stored in forest products, which is affected by the volume of manufactured products, the types of products manufactured, the use to which the products are put and the methods used to dispose of or recycle them. Tracking net changes to the forest products pool requires consideration of factors described in this section and which have been built into the CFS Carbon Budget Models (CBM-CFS2 and CBM-FPS) described in section 9 below.

### 8.1 Determining initial contributions to the forest products carbon pool

This can be done in two ways: 1) based on logging volume, or 2) based on mill output.

The **logging volume method** can be used if the use the timber logged is going to is known. First, an appropriate utilization rate must be applied to the volume of timber logged (the CFS Carbon Budget Model uses figures of 80-85% of merchantable stem volume). Then, a number of assumptions must be made about what happens to that wood. The CBM-FPS describes a series of assumptions for several different forest products. Here is one of the more complex ones for illustrative purposes (Kurz *et al* 1992):

"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.”

More accurate assumptions could be made based on local uses but this gives an example of the level of detail used in the CFS model.

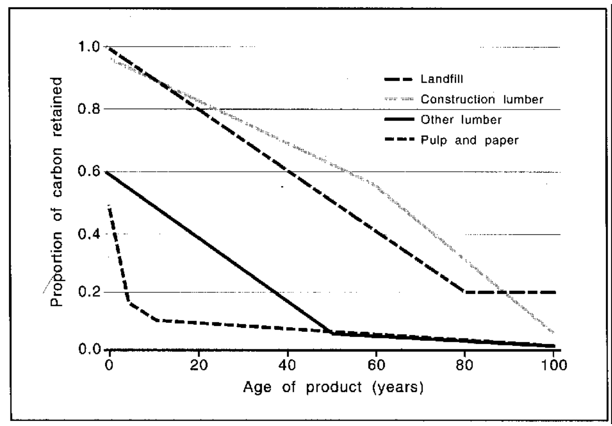
The **mill output method** involves simply recording the volume of output from the various mills in a particular FMU. This method saves having to make the various assumptions described above, but introduces complexities of its own. For one thing, factors to convert weights of different forest products into weights of carbon will be needed. As well, a number of potentially complicated questions about the flow of raw timber into and out of a particular FMU will have to be answered. How much of the timber logged in a particular forest is processed within that particular district and how much is exported? How much of the wood run through a particular mill or mills whose production is being tracked comes from the forest management unit and how much comes from elsewhere? In some districts this may be relatively simple while in other areas these questions can be extremely difficult to answer.

## 8.2 Forest product decay rates

Forest products decay at various rates with carbon returning to the atmosphere. Figure 2 is reproduced from the report describing the assumptions that were used in the CFS Carbon Budget Model (Kurz *et al* 1992). It shows how different forest products have different life expectancies as well as different initial utilization rates.

The model assumes that pulp logs are converted to paper at an approximate average efficiency of less than 50%, and that roughly 50% of what is manufactured is lost in the first year. The model makes a variety of different assumptions about what happens to the carbon that leaves a particular product pool – some of it decomposes, some is used for bioenergy, some is recycled, and some ends up in landfills where 20% of what is dumped will retain its carbon indefinitely. Construction lumber, by contrast, has a much higher utilization efficiency as well as a longer life span and it takes 60 years for carbon losses to reach 50%.

**Figure 2:** Carbon retention curves for three forest product categories (construction lumber, other lumber, and pulp products) and for forest products discarded in landfills.




(Source: Kurz *et al* 1992)

The CBM-FPS factors in energy and other emissions resulting from active forest management including site preparation, planting, fertilization, thinning, logging, transport to the mill, processing, and transport to markets. To do this, it requires additional mill and sector data that quantify these activities – such data, although typically proprietary, are usually readily available. These emissions may have significant impacts on the net (total) carbon budgets of the local operation and at the national scale (Apps *et al* 1999).

# 9. Carbon Budget Modelling

Carbon budget models are useful and important for at least three distinct reasons:

1) they allow managers to make educated estimates about changes taking place in carbon pools that cannot be readily measured

directly, especially soil carbon pools;

2) they allow managers to compare different management scenarios to better understand the impact of management decisions on carbon storage in forests; and

3) they permit managers to project these values into the future.

There is an additional function that is drawing increasing attention in the climate change science community; namely projecting the possible or likely impacts of climate change on forests, forest health and forest carbon storage. In effect, these models can include scenarios that factor in large-scale changes beyond the control of the forest manager but that offer the manager some guidance as to possible adaptive strategies.

As always, a model is only as good as its input and the assumptions used to run it. Even if the inputs and assumptions are highly accurate, there is always the potential that unforseen events or changes will intercede to ensure that reality differs from the model. Even though the predictive capacity of a model may be weak (especially over the 100-years-plus time frames used) they are still very useful in assessing present management options.

There are many carbon budget models in use around the world. They each have their distinctive features, require different inputs to run them, use different assumptions to project carbon trends into the future, and provide different degrees of coverage in terms of what is included and what is not included.

This section provides a brief introduction to the Carbon Budget Model developed by the Canadian Forest Service. This is not to say that it is the only or necessarily the best model that exists, but it is discussed here because it is most likely to be accessible to forest managers across Canada. The model has been tested and applied in a number of different situations in Canada, and continues to undergo development for Canadian conditions.

## 9.1 The CFS Carbon Budget Model

The Carbon Budget modelling framework is described in detail in reports that are available from the Canadian Forest Service (e.g., Kurz *et al* 1992; Kurz and Apps 1999; Apps *et al* 1999). Briefly, "it estimates the C stocks contained in, and C flows among, forest biomass, soils, and product using data derived from forest inventories, ecosystem classifications, soil surveys, and other government and industry statistics. Annual forest growth and soil decomposition for representative stand types are simulated using empirical relationships. The effects of disturbances (principally wildfires, insect attacks, and harvesting) on forest age structure and on C releases to the atmosphere and forest floor are calculated on a 5-year cycle" (Price *et al* 1997).

In the most recent version, CFS's modelling framework has two components: Carbon Budget Model - Canadian Forest Sector 2 (CBM-CFS2 which accounts for changes in carbon pools in the forest ecosystem, i.e., NEP and NBP) and Carbon Budget Model - Forest Product Sector (CBM-FPS which accounts for changes in forest product carbon pools as well as energy use and energy production – bioenergy – within the forest sector). The CBM framework was initially developed and used in order to estimate forest sector carbon budgets for Canada as a whole. The model suggests that Canada's forest was a significant carbon sink from 1920 through to the early 1970s after which it became a net source, losing about 69 Mt C per year from 1985 to 1989 (Forest Sector Table 1998). This change was due mainly to the increased occurrences of wildfires and insect infestations beginning in the 1970s (Kurz and Apps 1999).

## 9.2 Local level applications of the CFS Carbon Budget Model

The CBM framework (CBM-CFS2 and CBM-FPS) was modified for application in the area covered by the **Foothills Model Forest** to use local, rather than national-scale, data. The modified model was used to simulate and compare the carbon storage over 250 years, from 1958 to 2238, according to a number of different scenarios, comparing different management scenarios (including an "unmanaged" scenario with no harvesting taking place) as well as testing the sensitivity of different assumptions used to run the model. The study demonstrates that managing a forest for wood production may lead to greater carbon storage than occurs in a natural forest ecosystem if the management regime maintains a rotation period that is longer than the natural disturbance cycle. The model "base case" is based on a reported 50-year natural disturbance cycle in the Foothills area although more recent work (and the results of the model itself) suggest that this may be a significant underestimate (Price *et al* 1997).

The generic model has also been run in a number of **hypothetical forests** of 100,000 hectares each comprising representative landscapes of coastal and interior B.C. as well as the boreal forest in Ontario (Kurz *et al* 1998). In each case, a comparison was made between an "unmanaged forest" having a natural disturbance cycle between 80 and 400 years and a managed forest with a rotation age of 100-400 years. At risk of great simplification, the model found that where rotation age is the same as the natural disturbance cycle there is a tendency to see a moderate decline in carbon storage, principally because harvesting is directed preferentially at older stands while fire attacks all stands over a minimum threshold density. Where the rotation age is significantly shorter than the natural disturbance cycle (such as in coastal B.C. forests) the management regime can reduce carbon by as much as 42%.

### 9.3 A universally applicable carbon budget model

The work done above has demonstrated that the CFS Carbon Budget Model is able to be applied at the FMU level. The model itself, however, is not considered "user-friendly" and it cannot be applied in a particular forest situation without the active involvement of the model designers. With some relatively modest modifications, however, it could be made available in a "turn-key" version that could be easily used by others (Apps, pers. comm.).

# 10. Forests, Sustainable Forest Management and Climate Change

In the end, carbon budget modelling will only make real sense to forest managers if there is something that they can do about it; practical measures that forest managers can undertake that will help to address climate change. While many such measures do exist, it is also important to sound a few cautionary notes about general limitations on the role of forests in mitigating climate change.

**Saturation:** The overall value of forests in mitigating climate change is limited by the land available and the practical maximum of carbon that can be stored on the land (Schlamadinger & Marland 2000). This means that forest management activities offer at best a transition strategy towards genuine low-carbon futures; but there is a risk that too much attention on forest sinks may delay progress on more effective long-term actions.

**Impermanence:** Carbon storage in forests is potentially reversible due to future natural and anthropogenic activities, and this feature distinguishes them from activities that reduce fossil fuel use (IPCC SRLUCF 2000). For this reason, a tonne of sequestered carbon should not be considered equivalent to a tonne of avoided emissions.

The Kyoto Protocol (although its terms have yet to be defined) seems likely to provide credit for activities that provide a benefit during the first commitment period (2008-2012) but that may not necessarily retain this benefit over the long term. An example might be the establishment of fast-growing plantations which can sequester large amounts of carbon over the short term (several decades), but it is precisely the fast-growing characteristic of these plantations that makes them especially vulnerable to the issues of saturation and impermanence.

There are, however, a variety of forest management activities that offer genuine opportunities to improve the ability of forests and forest products to store carbon over the long term (>100 years). They include:

- Managing to a longer rotation age thereby increasing the overall percentage of high-volume forests on the land base;
- Selection cutting or commercial thinning; removing some forest products while leaving a high on-site volume;
- Protecting forests from fire, disease and insects;
- Establishing protected areas;
- Avoiding deforestation due to land conversion and road construction;
- Silvicultural activities that enhance and protect soil carbon;
- Establishing new forests, especially shelterbelts and other lands put into permanent forest cover;
- Promoting urban forests; and
- Changing the forest product mix to favour more long-lived products.

Other measures involve direct reductions in fossil fuel use such as promoting the use of trees for biomass energy and improving energy efficiency throughout the forest product chain, all the way from site establishment to logging, transportation, manufacture, marketing, consumption, recycling and disposal. Many of the forest management measures listed above provide timber revenues although they don't necessarily maximize the direct revenue per hectare. Most of them provide ancillary social, non-timber economic and/or biodiversity benefits. All of them are part of the "mix" of measures that forest managers might consider in moving towards sustainable forest management and they all have the potential to provide long-term environmental benefits through enhanced carbon storage.

# 11. Key Messages and Recommendations

### To forest managers:

1. *Measuring carbon and carbon fluxes at the forest management unit level is not technically difficult and much can be done with data that is readily available to most forest managers.*

2. *Although initial measurements are likely to be somewhat imprecise and may not include all carbon pools, that does not invalidate their usefulness to forest managers who wish to incorporate an awareness of and sensitivity to climate change issues in their assessments, plans, monitoring and reporting.*

3. *Forest managers should report on the best available information, rather than waiting for "perfect" information to become available. Reporting now is the best way to generate the commitment to refine and improve upon initial estimates.*

4. *Several reports, available from the Canadian Forest Service's Northern Forest Centre, provide enough information to get started. "The carbon budget of the Canadian forest sector" (Kurz et al 1992, Information Report NOR-X-326) provides an excellent overview of the CFS Carbon Budget Model, while "A soil profile and organic carbon data base for Canadian forest and tundra mineral soils (Siltanen et al 1997) provides the necessary data on regional soil profiles. Other reports include, "A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector" (Kurz and Apps 1999) and "Carbon budget of the Canadian forest product sector" (Apps* et al *1999. Carbon conversion factors are*

*included in Figure 1 above (p.5). The other information needed to get started – volume of timber, growth yield curves, information about logging and natural disturbances – must be obtained locally.*

5. *There are several forest management measures that can augment the ability of forests to store carbon, and that are consistent with sustainable forest management. Long-term approaches that increase the overall storage of carbon (measured as tonnes/hectare/year, averaged out over a century or more) are more valuable than approaches that focus primarily on increasing the rate of short-term sequestration.*

### To the Model Forest Network:

6. *The Model Forest Network is well situated to play an important role in promoting the development of a universal carbon budget model that could be easily used with commonly available information by any forest manager. The Canadian Forest Service already has most of the elements needed to create a credible, easy-to-use universal model; and the support of and collaboration from the Model Forest Network could help to make this a priority.*

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## 13. References

------ (1992) United Nations Framework Convention on Climate Change.

Apps, M.J., W.A. Kurz, S.J. Beukema, and J.S. Bhatti. 1999. Carbon budget of the Canadian forest product sector. *Environmental Science and Policy* 2: 25-41.

Apps, Michael J. and Marsden, Jenni (eds.) (2000) The Role of Boreal Forests and Forestry in the Global Carbon Budget (Abstracts). Canadian Forest Service, May 2000.

Binkley, C.S., M.J. Apps, R.K. Dixon, P. Kauppi, and L-O. Nilsson. 1998. Sequestering carbon in natural forests. *Critical Reviews in Environmental Science and Technology* 27: S23-45.

Canadian Council of Forest Ministers (1997) Criteria and Indicators of Sustainable Forest Management in Canada: Technical Report. Natural Resources Canada, 1996.

Forest Sector Table (1998) Foundation Paper: A Survey of the Forest Sector and Forest Sector Options. Natural Resources Canada, October 1998.

Forest Sector Table (1999) Options Report: Options for the Forest Sector to Contribute to Canada's National Implementation Strategy for the Kyoto Protocol. Natural Resources Canada, November 1999.

IPPC. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, Organization for Economic Cooperation and Development and International Energy Agency.

IPCC (2000) Special Report on Land Use, Land-use Change and Forestry, Intergovernmental Panel on Climate Change, 2000.

Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J. (1992) The carbon budget of the Canadian forest sector: Phase I. Natural Resources Canada Information Report NOR-X-326, 1992.

Kurz, Werner A. And Apps, Michael J. (1999) A 70-Year Retrospective Analysis of Carbon Fluxes in the Canadian Forest Sector. *Ecological Applications* 9(2), pp 526-547.

Kurz, Werner A., Beukema, Sarah J. and Apps, Michael J. (1998) Carbon Budget Implications of the Transition from Natural to Managed Disturbance Regimes in Forest Landscapes. Mitigation and Adaptation Strategies for Global Change 2, pp 405-421.

Kurz, Werner A. (1999) Assessing Options for Measurement of Verifiable Changes in Carbon Stocks from reforestation, Afforestation, and Deforestation and Other Potential Forestry Activities. Prepared by Essa Technologies Ltd. For the Sinks Table, June 22, 1999.

Mahendrappa, M.K. and Pitt, C.M. (2000) Organic Horizon Thickness: An Indicator of Sustainable Forest Management in the Maritime Provinces. Final Report on Criteria and Indicators Group 4 - Carbon Sequestration in the Forests. Submitted to the Fundy Model Forest. March 2000,.

Price, David T., Apps, Michael J., Kurz, Werner A., Wesbrook, Michael, and Curry, R. Sean (1994) A “Model Forest Model”: Steps Toward Detailed Carbon Budget Assessments of Boreal Forest Ecosystems. *World Resources Review*, Vol. 6, No. 4, 1994, pp 461-476

Price, David T., Mair, Ralph M., Kurz, Werner A., and Apps, Michael J. (1996) Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study. *NATO ASI Series*, Vol I 40 pp 279-292

Price, D.T., Halliwell, D.H., Apps, M.J., Kurz, W.A., and Curry, S.R. (1997) Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. *Canadian Journal of Forest Research* 27: pp 2005-2016

Price, David T., Apps, Michael J., and Kurz, Werner A. (1998) Past and Possible Future Carbon Dynamics of Canada’s Boreal Forest Ecosystems. From G.M. Kohlmaier, M. Weber and R.A. Houghton (eds), Carbon Dioxide Mitigation in Forestry and Wood Industry, 1998, Springer, Berlin Heidelberg, pp 63-88.

Robinson, G.C., Peterson, E.B., Smith, S.M. and Nagle, G.S. (1999) Estimating the carbon sequestration associated with reforestation in western Canada. Submitted by Nawitka Renewable Resource Consultants to the Forest and Sinks Tables, June 11 1999.

Schlamadinger, B. and Marland, G. (2000) Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol. Pew Center on Global Climate Change, June 2000.

Siltanen, R.M., Apps, M.J., Zoltai, S.C., Mair, R.M. and Strong, W.L. (1997) A soil profile and organic carbon data base for Canadian forest and tundra mineral soils. Canadian Forest Service, Northern Forestry Centre, 1997.