Mitigation and Adaptation Strategies for Global Change (2006) 11: 33–43

DEVELOPING CANADA'S NATIONAL FOREST CARBON MONITORING, ACCOUNTING AND REPORTING SYSTEM TO MEET THE REPORTING REQUIREMENTS OF THE KYOTO PROTOCOL

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(Received 18 June 2003; accepted in final form 1 July 2004)

Abstract. The rate of carbon accumulation in the atmosphere can be reduced by decreasing emissions from the burning of fossil fuels and by increasing the net uptake (or reducing the net loss) of carbon in terrestrial (and aquatic) ecosystems. The Kyoto Protocol addresses both the release and uptake of carbon. Canada is developing a National Forest Carbon Monitoring, Accounting and Reporting System in support of its international obligations to report greenhouse gas sources and sinks. This system employs forest-inventory data, growth and yield information, and statistics on natural disturbances, management actions and land-use change to estimate forest carbon stocks, changes in carbon stocks, and emissions of non-CO_2 greenhouse gases. A key component of the system is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). The model is undergoing extensive revisions to enable analyses at four spatial scales (national, provincial, forest management unit and stand) and in annual time steps. The model and the supporting databases can be used to assess carbon-stock changes between 1990 and the present, and to predict future carbon-stock changes based on scenarios of future disturbance rates and management actions.

Keywords: accounting, carbon budget model, CBM-CFS, greenhouse gas emissions, Kyoto Protocol, monitoring, natural disturbances, reporting, NFCMARS

1. Introduction

Canada contains about 10% of the world's forest area. The people of Canada, represented by provincial, territorial and federal resource-management agencies, own the majority of Canada's forests. Reporting requirements of the Kyoto Protocol and other international agreements contribute to an increased demand for information on Canada's forests, and on the impacts of human activities such as land use and land-use change on these forests. Forest ecosystems are large stores of carbon. Depending on the stage of forest stand development, a stand can be either be removing carbon from the atmosphere (sink) or releasing carbon (source). A forested landscape is comprised of many stands in different stages of development. The net carbon balance of the landscape can be determined by integrating the dynamics of all stands.

This paper provides a general overview of the forest information requirements resulting from the 1997 Kyoto Protocol and from the 2001 Marrakesh Accords, which elaborate the rules of the Protocol. The paper outlines the plans and ongoing activities towards the development of Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS), and provides an example of how national forest information requirements can be met by building on existing forest information systems.

2. Forest Information Requirements for Kyoto Protocol Reporting

Developed countries that ratify the Kyoto Protocol commit to limit net greenhouse gas emissions and to report their annual greenhouse gas balance according to the rules of the Protocol as elaborated in the IPCC Good Practice Guidance for Land Use, Land-use Change and Forestry (IPCC 2003). The Kyoto Protocol, which entered into force February 16 2005, represents an internationally binding agreement. The Protocol recognizes the role of land use, land-use change and forestry (LULUCF) in contributing both sources and sinks to national greenhouse gas balances. The protocol outlines a two-step process in which countries first define and identify the areas subject to certain land-use and land-use-change activities, and then quantify the net greenhouse gas sources and sinks on these areas. To quantify the impacts of land-use change, specifically the conversion of forests to non-forests and vice versa, Article 3.3 of the Kyoto Protocol specifies that countries must identify those areas affected by afforestation, reforestation and deforestation since 1990, and then determine the carbon-stock changes (and non-CO_2 greenhouse gas emissions) on these areas during the first commitment period, from January 1, 2008 to December 31, 2012.

For the first commitment period, Article 3.4 of the Protocol also provides countries with the option to include certain land-use and forestry activities in their national accounts of greenhouse gas sources and sinks. Countries must decide by the end of 2006 whether to account for the carbon-stock changes and non-CO_2 emissions resulting from one or more of the activities specified under Article 3.4 (forest management, cropland management, grazing-land management and revegetation). Forest management is defined in the Marrekesh Accords as "a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner" (FCCC/CP/2001/13/Add. 1, English, p. 58). Countries that choose to include forest management in their greenhouse gas accounts for the first commitment period must identify areas subject to forest management and then account for carbon-stock changes (and non-CO_2 greenhouse gas emissions) on those areas during the commitment period.

After applying a series of reporting guidelines, accounting rules and country-specific caps (that are beyond the scope of this paper), the resulting net balance of sources and sinks will be applied to a country's national account. If LULUCF activities contribute a net sink, the balance will help a country to meet its reduced-emissions target, while a net source will be added to the country's emissions from fossil sources.

Compliance with the monitoring and reporting requirements of the Kyoto Protocol will necessitate substantial revisions to most countries' forest and land-use inventories. The Kyoto Protocol, as elaborated in the Marrakesh Accords, requires that countries define the geographic boundaries of the areas encompassing the units of land subject to Article 3.3 activities and the lands subject to Article 3.4 activities. Countries could choose these strata in such a way that estimation of the areas subject to these activities is facilitated and uncertainties of estimates obtained for these areas are minimized. In Canada, for example, population density and human access to forests differ greatly between regions. Pre-stratification of the land area could be based on the extent and type of expected land-use and land-use-change activities.

Perhaps the biggest challenge for most countries will be meeting the requirement for an inventory of human-induced afforestation, reforestation and deforestation activities since 1990, at a resolution of 0.05 to 1 hectare (the size range specified in the Marrakesh Accords). Although most nations will likely choose the upper bound of this range, estimating past and future land-use changes with a one-hectare resolution will present a formidable challenge, especially for large countries. The development of statistically valid sampling protocols, including the pre-stratification of the country into regions with different levels and types of land-use-change activities, may improve the efficiency of monitoring and reporting programs.

Once the areas subject to land-use change under Article 3.3 and, if elected, activities under Article 3.4 have been identified, estimates of changes in all ecosystem carbon stocks and the non-CO_2 greenhouse gas emissions on these areas are required for each year of the first commitment period. The Kyoto Protocol requires that carbon-stock changes in aboveground and belowground biomass, in litter, in dead wood and in soil carbon be estimated. Since it is not feasible to measure carbon-stock changes on an annual basis, national accounting frameworks could support the monitoring and reporting needs through a combination of measurements and modeling.

The remainder of this paper will outline the ongoing development of Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS). The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol reporting requirements for the first commitment period assume that the carbon contained in harvested wood products is at steady state and that additions merely replace losses from existing carbon stocks. For the first commitment period, and in accordance with the reporting guidelines, it is assumed that carbon in harvested biomass is released when the trees are removed from the ecosystem. Should harvested wood products be included in the reporting requirements of future commitment periods, the system developed to track carbon in harvested wood products in Canada (Apps et al. 1999) will be updated accordingly.

3. Canada's National Forest Carbon Monitoring, Accounting, and Reporting System

3.1. System requirements

The purpose of Canada's NFCMARS is to estimate carbon-stock changes and non-CO_2 greenhouse gas emissions in Canada's managed forest. The system is designed to estimate past changes, e.g. from 1990 to the present (monitoring), and to predict, given various assumptions, carbon-stock changes in the next two to three decades (projection). The system therefore must be able to process data on past forest conditions and forest changes into estimates of carbon-stock changes, as well as simulate future forest changes based on assumptions about forest management, natural disturbances and other ecological processes.

The development of Canada's forest carbon accounting system currently focuses on four spatial scales (Figure 1):

1. *National scale* (10^8 ha) to support international reporting of carbon-stock changes, and to integrate information for the entire managed forest of Canada.
2. *Regional and provincial scale* (10^7 ha) because forest policy decisions in Canada are provincial responsibilities and the consequences of alternative policy choices need to be evaluated at that scale.
3. *Operational management units* (10^5–10^6 ha) are the scale at which operational forest management decisions are made. To contribute towards increasing forest carbon stocks and reducing carbon losses, forest managers require tools with which to assess the impacts of alternative management options on carbon stocks (Kurz et al. 2002).
4. *Stand level* (1–100 ha) analyses are required for calibration and verification of models through comparison with plot-level measurements.

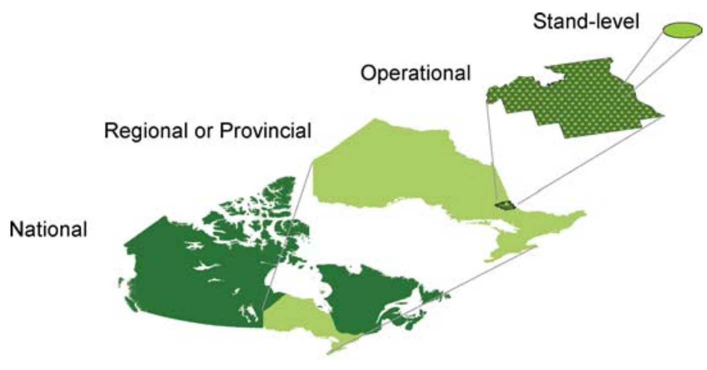

Figure 1. The Carbon Budget Model of the Canadian Forest Sector is operating at four spatial scales and uses the best available information on forest inventories, growth and yield, natural disturbances, forest management activities and other ecosystem processes at each of these scales.

To ensure consistency of the estimates across spatial scales, the model uses the same basic principles and accounting rules at each scale. The spatial resolution and aggregation of the input data, however, differ between scales. At the scale of operational management units, all forest-cover polygons can be represented as separate stands. At the national scale, stands with similar attributes in a specified area are aggregated. The impacts of the analysis scale and aggregation on carbon-stock estimates are the subject of ongoing research activities.

3.2. Carbon budget model of the Canadian forest sector (CBM-CFS2)

At the core of the system is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2), a stand- and landscape-level model of forest-ecosystem-carbon dynamics (Kurz et al. 1992; Kurz and Apps 1999). The model has been applied to analyze past and future changes in forest biomass and dead organic matter carbon stocks in Canada's entire forest, in the managed forest, in individual provinces or regions and at the scale of operational units. The CBM-CFS2 has been used to explore possible future scenarios that assume a range of natural-disturbance rates, harvest rates, growth rates, decomposition rates, and combinations thereof.

The CBM-CFS2 is undergoing extensive revisions in preparation for its role in the NFCMARS and for its application at the operational scale. The model was developed as a research tool, but work is in progress to make the model operational and easily accessible to analysts. The spatial resolution of the model has greatly increased, allowing the explicit simulation of millions of stands in annual time steps. When used in a monitoring role to assess past changes in carbon stocks, the model can be spatially explicit and represent each polygon in a forest inventory with a corresponding record. Revisions to model–user interfaces, data pre- and post-processing tools and the underlying database infrastructure are in progress.

At the stand level, the revised CBM-CFS tracks the dynamics of aboveground and belowground biomass carbon pools, as well as the dynamics of several dead organic matter pools that represent standing dead trees, woody debris, litter and soil carbon. The model accounts for carbon uptake through biomass growth and for the transfer of biomass to dead organic matter pools through litterfall, tree mortality, management actions (e.g., harvesting, partial cutting), and natural disturbances (e.g., wildfire, insects). The model simulates the decay of all dead organic matter pools and the release of carbon associated with management actions (e.g., slash burning) and natural disturbances.

At the landscape level, the CBM-CFS2 accounts for changes in the age–class structure and the distribution of different forest types resulting from management actions, land-use changes and natural disturbances. The model integrates, through space and time, all carbon stocks and carbon-stock changes, and stores the relevant results in an output database.

For analyses at the operational to national scales, it is possible to report the carbon stocks and carbon-stock changes for the entire forest area or for specific areas, as required under various international reporting rules. For example, the Marrakesh Accords that elaborate the rules of the Kyoto Protocol require carbon-stock changes be reported for areas subject to land-use change involving forests (afforestation, reforestation and deforestation) since 1990, for areas subject to forest management, and for areas that come under both categories. The model tracks, for each record containing forest area, whether the land area is eligible for inclusion under the accounts of the Kyoto Protocol (i.e., Article 3.3 or 3.4) or under the accounts of the UNFCCC managed forest area. The same system can therefore be used to meet both the Kyoto Protocol and the UNFCCC reporting requirements for forests.

For land that has been deforested since 1990 and is now in an agricultural land-use category, the current plan is to account for carbon-stock changes using the agricultural carbon accounting models of Agriculture and Agri-Food Canada. A pilot project is underway to develop the procedures and model interfaces to permit the transfer of land-use change information between the forest and agricultural carbon accounting systems.

3.3. Forest inventory data

The information on the present or past forest condition in the area to which the model is applied is derived from forest-inventory systems. Depending on the scale of the application, these can be either detailed, spatially explicit inventories or non-spatial summaries for specific areas (such as the administrative or ecological strata for which carbon stocks will be reported). Forest inventories are obtained from federal compilations such as Canada's National Forest Inventory (Bonnor 1985; Lowe et al. 1994; Gillis 2001), provincial and territorial resource-management agencies, or the forest industry.

All older national forest inventories in Canada are based on data compilations from numerous source inventories, collected over a number of years, employing a range of methods and including areas that have changed over time. It is therefore inappropriate to attempt to infer carbon-stock changes from consecutive national forest inventories. Past regional or national analyses with the CBM-CFS2 have always combined a single inventory with information about stand dynamics and landscape-level management actions and natural disturbances.

Canada's new National Forest Inventory (NFI, Gillis 2001) is designed to monitor changes. Statistically valid assessments of forest attributes and their changes over time will be possible with the NFI. The NFI sample protocol is based on a grid covering all of Canada's land area. Large plots (2 × 2 km) will be established at grid intersections (20 × 20 km) and their characteristics will be recorded from either aerial photographs or remote sensing. Additional ground plots will be established at a subset of the sample plots to measure a range of plot attributes, including biomass and dead organic matter pools. The national grid system and the sampling protocols have been developed; plot establishment (photo and ground plots) has commenced in most provinces and territories, while other jurisdictions are at the planning stages. It is currently expected that all permanent sample plots will be established by 2006 and that photo-plots will be re-inventoried at 5-year intervals. Re-measurements of ground-plots are scheduled at 10-year intervals.

The current design for the forest carbon accounting framework calls for use of the "best available" inventory information at various spatial scales (Figure 1). By the end of the first commitment period (Dec. 31, 2012), the NFI will provide much of the inventory information required for the C-stock analyses at the national scale. The accounting system will be designed such that it can, for specific areas, also make use of provincial or industry forest inventories in which coverage goes beyond the NFI plots. The implementation of the forest carbon accounting system will ensure that all required areas are accounted and that no double counting occurs.

Remote sensing of forest area and its characteristics will play an important role in Canada's forest carbon accounting system. For example, the Earth Observation for Sustainable Development (EOSD) team of the Canadian Forest Service, in collaboration with the Canadian Space Agency (CSA), is developing a high-resolution (30 m pixels, Landsat 7) forest-cover map of Canada for the year 2000 (Wood et al. 2002). Such information can be used to enhance forest inventories and to extend inventories to areas that are currently not or only poorly covered, such as non-timber-productive forests and parks. Although some of these areas may not be included in the reporting under the Kyoto Protocol, quantifying their carbon stocks and carbon-stock changes is of scientific interest.

Remote sensing will also play an important role in the detection of forest changes (such as harvesting, wildfire and insect impacts) and land-use change (Leckie et al. 2002). Developing and maintaining a database on land-use changes (afforestation, reforestation and deforestation) for Canada, as required under Article 3.3 of the Kyoto Protocol, is a major initiative involving close cooperation of Natural Resources Canada/Canadian Forest Service, Environment Canada, Agriculture and Agri-Food Canada, Statistics Canada and resource-management agencies in provinces and territories.

The Canadian Forest Service, in cooperation with provincial and territorial resource-management agencies, has developed and is maintaining a spatial database on large (>200 ha) fires, which cover about 97% of the area burned in Canada for the period 1959 to present (Stocks et al. 1996; Stocks et al. 2002). Databases on insect disturbances are also being compiled. This information on natural disturbances is essential for the simulation of the impacts of fires and insects on carbon dynamics (Kurz and Apps 1999). In combination with information on annual fire weather conditions, statistics on area burned have also been used to estimate annual emissions that result directly from forest fires (Amiro et al. 2001).

3.4. Biomass dynamics

During the past decades, government agencies and the forest industry in Canada have established more than 40,000 permanent sample plots and over 10,000 temporary sample plots. These provide data on the dynamics of forest stands in Canada. In many provinces, the growth and yield information is linked to ecological and site-classification systems, thus allowing for the regional extrapolation of estimates.

Yield tables, empirical yield models and other growth and yield modeling approaches are primary sources of information on stand dynamics currently used in the CBM-CFS2. This ensures that the model is data driven and that the analyses about future carbon-stock changes are consistent with the regional and provincial timber-supply analyses and other quantitative forest-planning processes.

The disadvantage of empirical yield functions is that they generally are not responsive to changes in environmental conditions. Between-year variations in growing conditions can result in deviations in the annual growth dynamics from those observed in the past. Development plans for the CBM-CFS2 include the ability to either incorporate the growth predictions from process models (e.g., Bernier et al. 1999) or to quantify the impacts of environmental variation such that empirical growth curves can be modified to reflect annual variation in growing conditions. Although the IPCC Good Practice Guidance states that the use of empirical growth functions is good practice it also suggests that "it is *good practice* to evaluate the potential influences of interannual variability in environmental conditions" to assess whether the use of empirical growth functions may lead to over- or under-prediction of carbon-stock changes (IPCC 2003, Ch. 4.2.3.7).

Growth and yield data usually quantify the dynamics of merchantable volume; carbon-stock estimates, however, are required for the total biomass pool. Expanding estimates of merchantable volume to stem wood, stem bark, branch and foliage biomass requires stand-level expansion factors. A group of Canadian Forest Service scientists is developing a system of equations for volume to biomass conversion, based on individual tree biomass-regression equations and permanent sample plot data from across Canada (M. Gillis, Canadian Forest Service, pers. comm.). The CBM-CFS2 uses this system of equations and parameters to convert stand-level volume data to estimates of aboveground biomass components.

The dynamics of belowground biomass (i.e., coarse and fine roots) are simulated based on functional relationships between aboveground and belowground biomass (Kurz et al. 1996). Following the observation that the CBM-CFS2 over-predicted belowground net primary production (Li et al. 2002), the approach to estimating fine-root production has recently been revised (Li et al. 2003).

3.5. Dead organic matter dynamics

Forest inventories typically do not include much information on dead organic matter carbon pools, which include litter, dead wood and soil C. The sampling protocol for the new NFI ground plots includes measurements of dead organic matter carbon pools. Some newer provincial and territorial inventories also contain relevant information on dead organic matter pools.

The CBM-CFS2 uses a simulation approach to link the dynamics of dead organic matter pools to the dynamics of forest stands. Biomass inputs are a function of stand dynamics and stand conditions. Decay rates in the model are simulated as a function of mean annual temperature and stage of stand development (Kurz and Apps 1999). The impacts of past disturbances and management actions also influence the size and composition of dead organic matter pools (Kurz and Apps 1999). The model tracks the dynamics of four pools, characterized by the type of biomass input and their turnover rates. To facilitate comparison between predicted and observed dead organic matter pools (e.g., Bhatti et al. 2000), the model is being revised to simulate twelve pools, including pools representing standing dead trees. Planned revisions to the model also include a review of decay rate assumptions in response to recent findings of long-term decomposition-rate experiments at sites across Canada (Trofymow et al. 2002).

National compilations of soil carbon information (e.g., Siltanen et al. 1997) do not contain information on current stand conditions or on past natural disturbances or management actions. Since each of these affects the composition and size of dead organic matter pools, it is difficult to compare model predictions against field-data compilations. A new national compilation of ecosystem carbon-stock information has been initiated that will include, where available, data on past disturbances and management actions as well as on the current stand conditions (Shaw et al. 2005). Measurements from ground plots in Canada's new National Forest Inventory will generate additional data on litter, dead wood and soil carbon in forest ecosystems across Canada. The representation of dead organic matter dynamics in the model will be refined as these regional data become available for calibration and validation of the model.

4. Conclusions

Meeting the information and reporting requirements of the Kyoto Protocol will necessitate new forest information systems, models and a well-coordinated national effort at obtaining data on land use, land-use change and forest management activities in Canada. While "demonstration of progress" on the implementation of domestic reporting and accounting systems is required by 2005 (FCCC/CP/2001/13/Add. 3, English, p. 14), the system must be operational by 2006 in order to generate estimates of carbon stocks, carbon-stock changes and non-CO_2 greenhouse gas emissions for the pre-commitment period report required under the rules of the Kyoto Protocol (FCCC/CP/2001/13/Add. 2 English, p. 58). The design of Canada's NFC-MARS anticipates that new data, better scientific understanding and refined ecosystem process models will become available in coming years. Analyses of model sensitivities and of uncertainties in overall estimates will guide the development of the system towards improved estimates of forest-carbon sources and sinks. The ongoing development process will involve continued consultation with federal departments, provinces, territories, forest industry, universities and other interested communities. For further information on the NFCMARS see http://carbon.cfs.nrcan.gc.ca.

Acknowledgements

The development of Canada's National Forest Carbon Monitoring, Accounting and Reporting System is supported in part through funding from the Climate Change Action Fund, Action Plan 2000 and the Panel on Energy Research and Development. The development of the CBM-CFS2 and the supporting infrastructure and science involves a large number of scientists and other experts in the federal government, in provincial and territorial resource-management agencies, in universities and in industry. Suggestions, support and data provided by those communities are greatly appreciated: without this continuing support, an integrating project of this scale would not be possible. We thank Bernhard Schlamadinger, Brian Stocks, Tony Lemprière, Evelynne Wrangler, Jim Wood and Monique Keiran for comments on a draft of this paper. We also acknowledge the constructive discussions with our co-authors during the preparation of the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry.

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