Spatially Explicit Forest Carbon Stock Change Accounting: Approach, Implementation, and Data Requirements

Graham Stinson, Werner A. Kurz, Sally Tinis, Dennis Paradine and Don Leckie
Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Canada.

Abstract

The Kyoto Protocol requires separate reporting of carbon (C) stock changes associated with land-use change (Article 3.3) and forest management (Article 3.4). National C accounting systems must therefore provide the capability to identify lands subject to different accounting rules and to track C stock changes on these lands. A spatially explicit approach to forest C accounting provides a framework for integration of spatial data and modelling tools so that the accounting requirements of the Kyoto Protocol can be met. A spatially explicit approach was tested on a 1.4 million-ha landscape in Canada using a spatially explicit version of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). CBM-CFS3 estimates C stocks and stock changes in above- and below-ground living biomass, dead wood, litter, and soil organic matter. The spatially explicit modeling approach used in the CBM-CFS3 enables detailed mapping of lands that are subject to the accounting rules in Article 3.3 and Article 3.4. Carbon stock changes can be estimated following Approach 3 for representing land areas (spatially explicit observations), as defined by the Intergovernmental Panel on Climate Change in the Good Practice Guidance for Land Use, Land-use Change and Forestry.

Key words: Forest carbon, carbon accounting, spatially explicit, Kyoto Protocol, land-use change

1. INTRODUCTION

Forest carbon (C) stock and stock change accounting is a relatively new discipline. Scientific research into landscape-level forest C dynamics and the role of forest ecosystems in the global C budget has been ongoing for some time, but the development of modeling tools and inventory methods capable of tracking forest ecosystem C fluxes over large landscapes with reasonable accuracy has only started recently. Industrialized parties to the 1992 United Nations Framework Convention on Climate Change (UNFCCC) have reported annually since the mid-1990s on emissions and removals from their managed forest areas and land-use change. With entry into force of the Kyoto Protocol in 2005, the bar has been raised with regard to national C monitoring, accounting and reporting requirements, and deadlines for reporting have been set. Nations will need to quickly develop national forest C accounting and inventory systems that incorporate the best available science and technology to meet the reporting requirements of the Kyoto Protocol and the Marrakech Accords in a manner that will stand up to international scrutiny.

Under the Kyoto Protocol, parties must report emissions by sources and removals by sinks of CO_2 and other greenhouse gases resulting from land use, land-use change and forestry (LULUCF) activities under Article 3.3, namely afforestation, reforestation, and deforestation that occurred since 1990. Parties that have opted to include forest management under Article 3.4 must also report emissions by sources and removals by sinks of CO_2 and other greenhouse gases on lands subject to forest management (FCCC/CP/2001/13/Add.1). In order to report these emissions and removals, a nation must first be able to identify lands that have been subject to activities under Article 3.3 and/or Article 3.4 since 1990. Accounting systems must then be able to track the fate of these lands through time, so that estimates of C stock changes during the 2008 – 2012 commitment period can be calculated.

The Good Practice Guidance for Land Use, Land-use Change and Forestry (GPG-LULUCF) provides detailed instructions on how C accounting may be carried out (IPCC 2003). One of the key challenges in the development of inventory and accounting systems for the LULUCF sector is the identification of lands that have been subject to activities under Article 3.3 and/or Article 3.4 since 1990. In Chapter 2, the GPG-LULUCF describes three approaches for representing land areas and tracking land-use changes. The most detailed approach, Approach 3, involves spatially explicit observations of land use and land-use change.

Although relatively simple conceptually, the spatially explicit approach is data intensive. The GPG-LULUCF indicates that data may be obtained either by sampling of geographically located points, complete wall-to-wall mapping, or a combination of the two. In all cases, the data requirements for spatially explicit monitoring of land use and land-use change and estimating emissions from sources and removals by sinks on these lands are considerable. In most countries, existing forest inventory systems will not meet the data requirements of a spatially explicit approach.

In this paper, we briefly describe the Canadian experience with Approach 3 in a pilot project undertaken as part of the development of the National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS) for Canada (Kurz and Apps, in press; Kurz et al. in this volume). The purpose of this paper is to describe the approach, implementation and data requirements. Numerical results will be published in the future.

2. APPLICATION OF THE SPATIALLY EXPLICIT APPROACH IN CANADA

As part of the development of Canada's NFCMARS, a pilot project was undertaken to determine the most efficient mix of approaches for representing land areas in the NFCMARS, and to develop and test spatially explicit modelling capabilities in the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). CBM-CFS3 is a dynamic simulation model that incorporates forest inventory and growth and yield data, as well as statistics on natural disturbances, land-use change, and forest management activities (Kurz et al. 1992; Kurz and Apps 1999; Kurz et al. 2002). The pilot project was also used to build direct linkages between remote sensing systems used to monitor deforestation and disturbance and the CBM-CFS3. The project demonstrates how land-use change data derived from remote sensing could be used in a spatially explicit C accounting framework, consistent with the GPG-LULUCF Approach 3 for representing land areas.

2.1 Pilot Project Study Area

The pilot project study area includes 1.4 million ha of predominantly forested landscape in the central interior of British Columbia, near the city of Prince George (Figure 1). This study area is an excellent test location because of the diversity of land uses in the area, including forestry and agriculture as well as urban and rural residential land uses. The study area is also situated in a region categorized as a "hotspot" in Canada's proposed National Deforestation Monitoring Stratification System. In this stratification system, hotspots are those regions that may have unusually high rates of land-use change or urban areas located in forested regions. The region surrounding the city of Prince George has had especially high rates of land-use change since 1990, with deforestation rates far exceeding the national average.

The study area is located at 54 ^{o}N and 123 ^{o}W on moderately flat terrain ranging in elevation from 750-1000 m and has a mean annual precipitation of 638 mm and a mean annual temperature of 2.6 ^{o}C. The study area is primarily located in the sub-boreal spruce biogeoclimatic zone (Meidinger and Pojar 1991). Dominant forest cover types include even-aged stands of lodgepole pine (*Pinus contorta*) or mixed lodgepole pine and hybrid white spruce (*Picea glauca* x *engelmannii*), with localized areas dominated by black spruce (*Picea mariana*) or trembling aspen (*Populus tremuloides*).

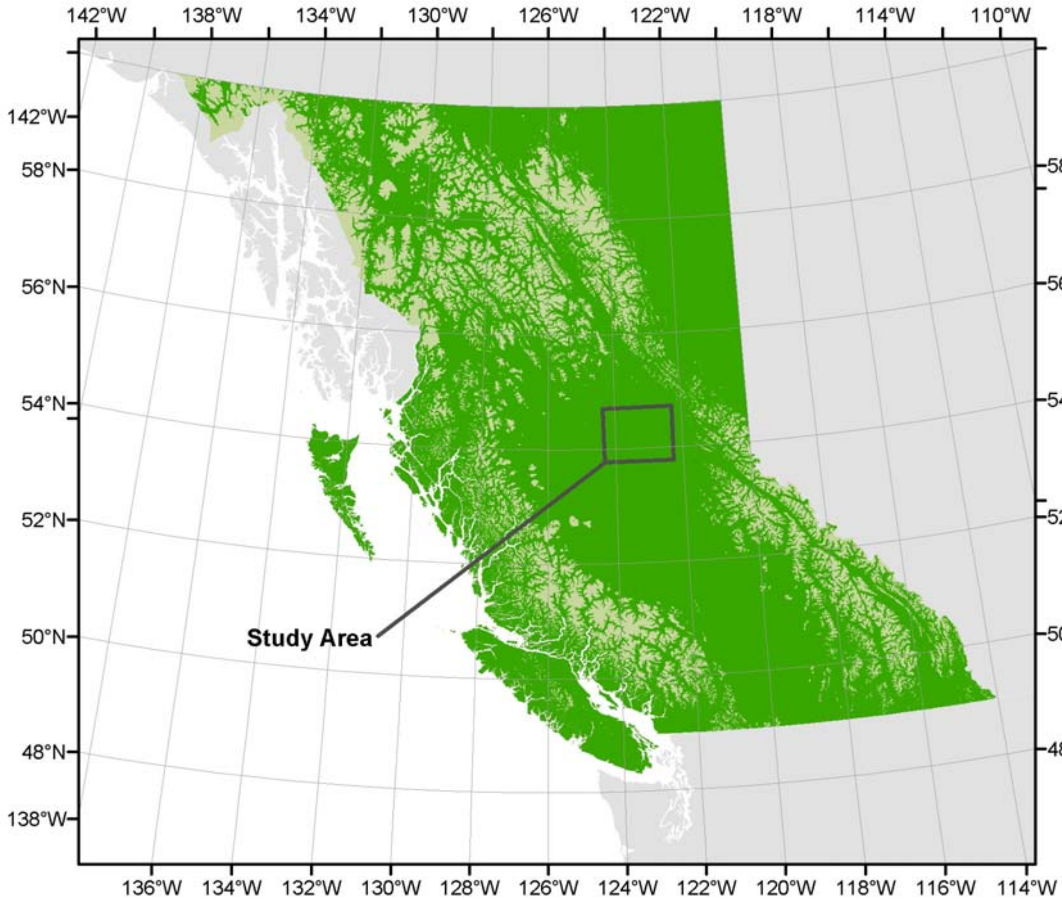

Figure 1. The Prince George pilot study area covers an area of approximately 1.4 million ha in central British Columbia (shown in green), Canada.

2.2 Methodology

Figure 2 summarizes the steps that were followed in the pilot project. First, satellite imagery from 1990 (Landsat 5 TM) and 1999 (Landsat 7 ETM+) was manually interpreted according to the Canadian Forest Service standard deforestation mapping methodology (Paradine et al. 2003) to generate a GIS coverage of all forest harvesting and deforestation events larger than 1 ha that occurred in the study area between 1990 and 1999. This dataset, supplemented by the forest inventory and other ancillary information, was then used to build a spatially explicit inventory of disturbance events for loading into a geodatabase constructed using ESRI ArcGIS. In this context, disturbances are events which cause an interruption of normal forest stand development, such as wildfire, insect outbreak, land clearing, harvesting, or forest management activities. All disturbance data generated in the change detection process were validated and revised where necessary. An independent accuracy assessment was also conducted.

A spatially explicit forest inventory for the study area with over 140 000 forest cover polygons was obtained from the provincial forest management agency, and this was also loaded into the geodatabase. The forest inventory was then intersected with the disturbance events layer to

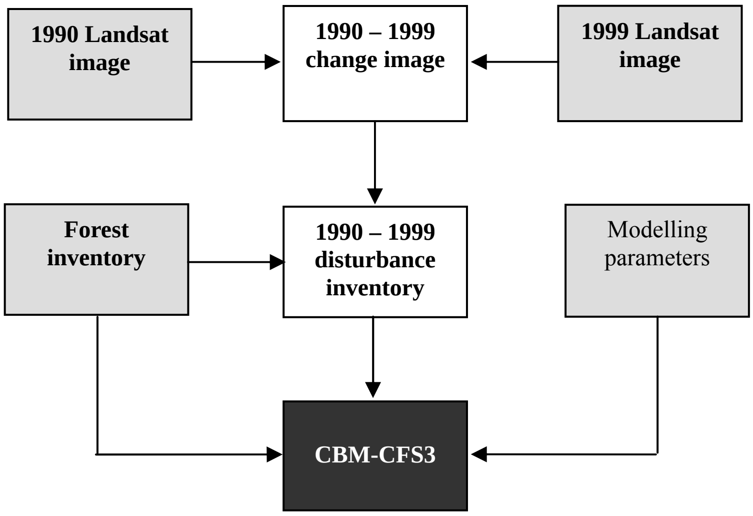

Figure 2. Prince George pilot project methodology overview flow diagram.

generate a layer of forest inventory polygons with unique disturbance histories, and to reference each event in the disturbance inventory to the appropriate forest inventory polygons (figure 3). Where the forest inventory was in disagreement with the remote sensing data, we considered the inventory to be in error. For example, if the remote sensing showed a harvest cutblock where the inventory did not, we assumed that the harvesting had indeed taken place and that the inventory simply had not yet been updated. The forest inventory and the disturbance inventory were then loaded into CBM-CFS3 along with a library of merchantable volume-over-age curves that describe growth and yield by forest type, site quality, and other classifiers. The CBM-CFS3 also uses parameters for the conversion of merchantable volume to total above- and below-ground biomass and other ecological parameters such as litterfall rates and dead organic matter decomposition rates.

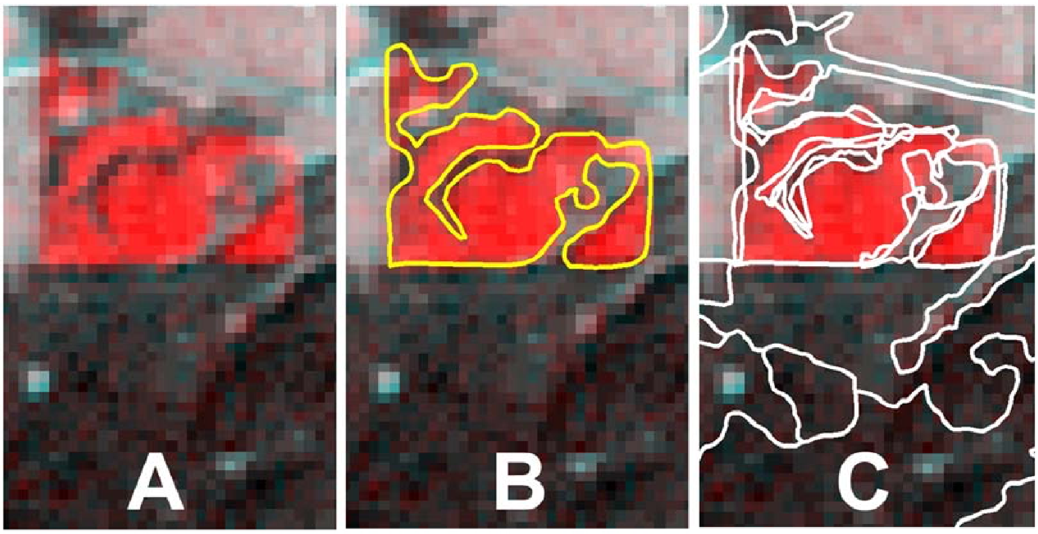

Figure 3. A change-enhanced image (A) highlights in red those areas where forest cover change occurred between 1990 and 1999. Change events are delineated (B) using a combination of manual and semi-automated methods and interpreters attribute the type of cover change (e.g. land-use change or forestry activity) and time of change by considering evidence from available ancillary information. The change events are then intersected with forest inventory polygons to produce a map of forest cover polygons with unique disturbance histories (C).

For this pilot project, a spatially explicit version of CBM-CFS3 was developed by adding capability in the model to track forest ecosystem C stocks and C stock changes in each individual forest cover polygon. The model treats each polygon as an individual stand, simulates its C dynamics, and summarizes C stocks and stock changes for user-defined reporting classes. Model output can be mapped at the same level of spatial detail as any other forest inventory attribute.

All spatial analysis steps are carried out as pre-processing steps in the GIS and only polygon ID and attribute information are passed to the model. The model preserves linkages between its attribute information and the spatial information in the GIS by maintaining the polygon ID values throughout the modeling process. Disturbance events are referenced to specific forest cover polygons in the simulations, so that the correct inventory records are disturbed and so that output can be loaded back into the GIS for analysis and display (Figure 4).

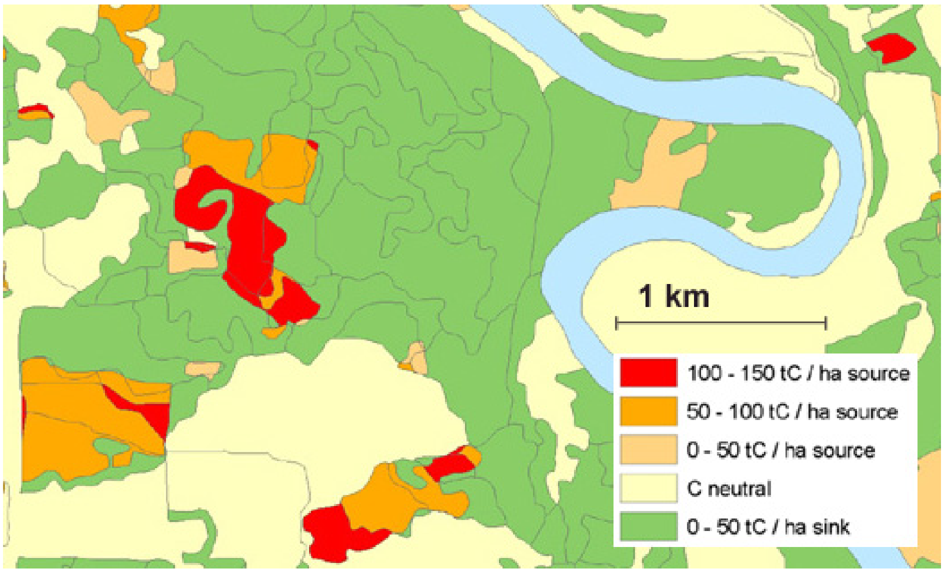

Figure 4. Results from the spatially-explicit version of CBM-CFS3 can be exported to GIS software to produce maps showing the location of C sources and sinks on the landscape. This example shows C sinks and sources in a small portion of the Prince George pilot study area located along the Nechako River.

Once all of the forest inventory, disturbance inventory and modeling parameters were loaded into CBM-CFS3, the model was used to initialize the inventory to the start of the simulation period and to calculate the initial C stocks. Where the exact state of the forest at the start of the simulation period was not known (i.e. where disturbances had occurred after 1990 and the inventory had since been updated), we used remote sensing analysis of the 1990 imagery to get broad classification information, such as general cover type and maturity class, and then made assumptions about the precise state of the forest at the start of the simulation period. For example, stands identified as mature conifer in the 1990 imagery were assumed to be 220-year-old lodgepole pine because this is the most common conifer cover type in the study area and harvest records indicate that most pine stands harvested in the study area are approximately of this age. CBM-CFS3 was then used to simulate the forest C dynamics forward in annual time steps through the 9-year simulation period, from 1991 through 1999.

Where exact dates for disturbance events were known or could be determined, those events were applied in the appropriate timesteps during the model simulations. For many disturbance events, however, the year of disturbance was not known. For example, where there is no record of a land-use change or disturbance other than that interpreted from the 1990 and 1999 satellite imagery, we cannot know the year in which an event took place; these events were each assigned to a timestep such that they were distributed evenly through the 9-year period. Records indicate that the area disturbed annually in the Prince George region remained relatively constant throughout the simulation period.

The model runs were conducted on a desktop PC running Microsoft Windows 2000 with an AMD Athlon XP 2500+ processor and 1 GB RAM. Several simulations were run to explore model sensitivities to assumptions made about initial conditions and disturbance event timing. Output from each simulation was used to generate reports of C stocks and stock changes and to produce maps of C stocks and stock changes for the study area.

3. DISCUSSION

The Prince George pilot project demonstrated that spatially explicit forest C stock and stock change accounting over large areas is possible with the CBM-CFS3 modelling framework. The pilot project also showed that spatially explicit C accounting can be conducted effectively by integrating remote sensing land-use change monitoring data with forest inventory and forest management data. The spatially explicit version of CBM-CFS3 maintains separate accounts of C stocks and stock changes on lands subject to Kyoto Protocol Article 3.3 and Article 3.4 accounting rules and provides results in a format suitable for loading into a GIS for further analysis and display.

The Prince George pilot project revealed important sources of uncertainty as well as some key technical concerns to be aware of where the spatially explicit approach is applied. As noted in the GPG-LULUCF, the spatially explicit approach is very data intensive. The Prince George pilot project study area was selected in part because of the availability of detailed, high-quality, spatially explicit forest inventory and other critically important data. Even so, we found that data gaps introduced considerable uncertainty to the C stock change estimates. The two principal data gaps that we encountered were: (i) incomplete information about the status of the forest at the beginning of the simulation period, and (ii) limited information on timing of disturbance events.

Uncertainty about the initial conditions of the forest can have a significant impact on the estimated C dynamics for many years into the simulation. This is particularly true when the forest is disturbed during the simulation period. The initial conditions of the forest influence not only the amount of C released at the time of disturbance, but also the C dynamics prior to and following disturbance. This data gap arises from the common practice of inventory agencies to discard pre-harvest or pre-disturbance forest polygon attributes when updating forest inventory data. Although remote sensing does provide some information about the pre-harvest or pre-disturbance status of the forest, it cannot tell us the age of the trees or the forest cover type as accurately as an inventory would. To reduce uncertainty in C stock change estimates for UNFCCC reporting and Kyoto Protocol accounting, pre-disturbance forest polygon attributes should be retained for analysis.

The second important data gap encountered was the limited information on disturbance event timing. When a change is detected by comparing remote sensing imagery from two dates, it is often not possible to determine the year during which the change occurred; it may only be possible to say that the change occurred sometime between the two image dates. Where possible, ancillary data were used to narrow the range of possible disturbance dates, and while some events in the pilot project could be referenced to a specific year, many others could not. The implications of this uncertainty are significant. This uncertainty is particularly important within the context of the Kyoto Protocol if the two image dates do not coincide with the beginning and the end of the commitment period. Deforestation events that occur before the commitment period have a much smaller impact on reported C stock changes during the commitment period than those that occur during the commitment period. At the landscape level, the uncertainty about event timing may also be significant, unless the rate of land-use change and the types of forest cover being cleared remain constant over time.

The Marrakech Accords define deforestation as the "direct human-induced conversion of forested land to non-forested land" (FCCC/CP/2001/13/Add.1). Areas that are temporarily unstocked as a result of human intervention or natural causes but are expected to revert to forest are considered forest and are therefore not areas of deforestation. Therefore it is important to determine whether a detected forest clearing is permanent (land-use change) or merely a temporary disturbance, such as a forestry clearcut. Data on context, shape, adjacency and ancillary information such as ownership or zoning are required to determine if forest clearings detected by remote sensing are deforestation as opposed to forest harvesting or other temporary clearing (Leckie et al. 2002a; Leckie et al. 2002b). A manual interpretation procedure is currently the most reliable way to integrate all relevant information into the interpretation process. The approach used in the Prince George pilot project involved manual deforestation interpretation combined with semi-automated harvest block delineation in a specially designed interpretation environment (Paradine et al. 2003). Using this approach, we were able to distinguish between land-use change and temporary forest disturbance.

In the event of deforestation, land is transferred out of the forest land-use category into a non-forest land-use category. In the Prince George pilot project, we did not explicitly move lands between land-use categories. Carbon dynamics following deforestation were simulated in the CBM-CFS3 by tracking the decomposition of dead wood, litter, and soil organic matter. We did not simulate any revegetation of the deforested sites. In Canada's NFCMARS, deforested lands will be transferred out of the forest C accounting system and passed to the appropriate accounting system for each unit of land. For example, forested land cleared for agricultural land-use will be transferred from the NFCMARS to Canada's National Carbon and Greenhouse-Gas Accounting and Verification System for Agriculture (McConkey et al. 2002; McConkey et al. 2005).

4. CONCLUSIONS

The Prince George pilot project confirmed that it is possible to carry out detailed, spatially explicit forest C accounting using the CBM-CFS3 accounting framework and that this approach is viable for a highly complex landscape of 1.4 million ha. Spatial data processing and C dynamics modeling challenges were overcome relatively easily, but acquiring all of the required data was difficult and expensive.

The principal strength of the spatially explicit approach is its conceptual simplicity. It provides a straightforward framework for integrating information from multiple sources. Having geographically referenced information in a forest C accounting system greatly simplifies the integration of this information with other sources of geographically referenced information. This also permits spatial cross-validation against independent forest inventory and/or remote sensing products.

The methodology used in this project has been developed specifically to work in the Canadian context. Within Canada, however, circumstances vary considerably, particularly with regard to data availability. The Prince George pilot study area is not representative of all of Canada; it is a region with high quality forest inventory data and unusually high rates of land-use change. The spatially explicit version of CBM-CFS3 is currently being used in other pilot projects in Canada to assess the feasibility of applying the spatially explicit approach in different settings, and to determine the most efficient mix of approaches for representing land areas in Canada's NFCMARS.

ACKNOWLEDGEMENTS

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) was developed, in part, with funding from the Federal Panel on Energy Research and Development (PERD). The development and testing of the spatially explicit version of the CBM-CFS3 was made possible by funding from Canada's Action Plan 2000 on Climate Change. Thanks to Will Burt, Mike Henley and Heather Brass for image interpretation and to Ruth Parnall and Greg Rampley for technical support. Thanks also to Tony Lemprière and Steve Glover for helpful comments on previous versions of this manuscript.

REFERENCES

IPCC (Intergovernmental Panel on Climate Change). (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. IPCC National Greenhouse Gas Inventories Programme Technical Support Unit. Institute for Global Environmental Strategies. Hayama, Japan.

Kurz, W.A. and M.J. Apps. (1999) A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications*, 9:526-547.

Kurz, W.A. and M.J. Apps. (in press) Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to meet the reporting requirements of the Kyoto Protocol. *Mitigation and Adaptation Strategies for Global Change*.

Kurz, W.A., M.J. Apps, T.M. Webb and P.J. McNamee. (1992) *The carbon budget of the Canadian forest sector: phase 1*. Information Report NOR-X-326, Forestry Canada, Northwest Region.

Kurz, W.A., M.J. Apps, E. Banfield and G. Stinson. (2002) Forest carbon accounting at the operational scale. *Forestry Chronicle*, 78:672-679.

Leckie, D.G., M.D. Gillis, and M.A. Wulder. (2002a) Deforestation estimation for Canada under the Kyoto Protocol: A design study. *Canadian Journal of Remote Sensing*, 28(5):672-678.

Leckie, D.G., N. Walsworth, J. Dechka and M. Wulder. (2002b) An investigation of two date unsupervised classification in the context of a national program for Landsat based forest change mapping. *Proc International Geoscience and Remote Sensing Symp*. 2002. Toronto, ON. CD-ROM.

McConkey, B. G., C. M. Monreal, T. Huffman, G. T. Patterson, J. A. Brierley, R. L. Desjardins, P. Rochette, M. R. Carter, M. Bentham, and S. Gameda. 2002. National carbon and greenhouse-gas emission accounting and verification system for agriculture (NCGAVS). In: Smith C.A.S. (ed.) *Soil Organic Carbon and Agriculture: Developing Indicators for Policy Analysis*. Proceedings of an OECD expert meeting. Ottawa, Canada. Agriculture and Agri-Food Canada, Ottawa and Organization for Economic Co-operation and Development, Paris.

McConkey, B.G., Brierley, J.A., Vandenbygaart, A., Huffman, T., Martin, T., Bentham, M., Desjardins, R.L, Monreal, C.M., Patterson, G.T., Rochette, P., Liang, B.C., Smith, W.N., de Grooijer, H., Gameda, S., Cerkowniak, D., and Boehm, M. 2005. Estimating Carbon Change for Canada with the National Carbon and Greenhouse-Gas Accounting and Verification System for Agriculture (NCGAVS). *Canadian Journal of Soil Science* (submitted).

Meidinger, D. and J. Pojar. (1991) *Ecosystems of British Columbia*. B.C. Ministry of Forests

Special Report Series No.6.

Paradine, D., D. Leckie, and S. Tinis. (2003) *Deforestation Interpretation Guide. Version 2.0* Natural Resources Canada, Canadian Forest Service. (draft document)

Wulder, M.A., W.A. Kurz and M. Gillis. (2004) National level forest monitoring and modelling in Canada. *Progress in Planning* 61:365-381.

Proceedings of Workshop on Practical National Forest Inventory Systems to Meet the Requirements of the Kyoto Protocol

Tokyo, 15-16 November 2004

Organized by
Forestry and Forest Products Research Institute, Japan

Co-organised by
Forestry Agency, Ministry of Agriculture, Forestry and Fisheries
Ministry of the Environment
Waseda University

Publisher;
Forestry and Forest Products Research Institute, Japan, March, 2005

Editors;
Mitsuo Matsumoto, machan@ffpri.affrc.go.jp
Hidesato Kanomata, kanomata@affrc.go.jp

Copies of this book may be obtained from Division of Policy and Economics, Forestry and Forest Products Research Institute, Japan
1 Matsunosato, Tsukuba, Ibaraki, 305-8687, Japan
Tel: +81-29-873-3211, Ex. 641 Fax: +81-29-873-3799

CONTENTS