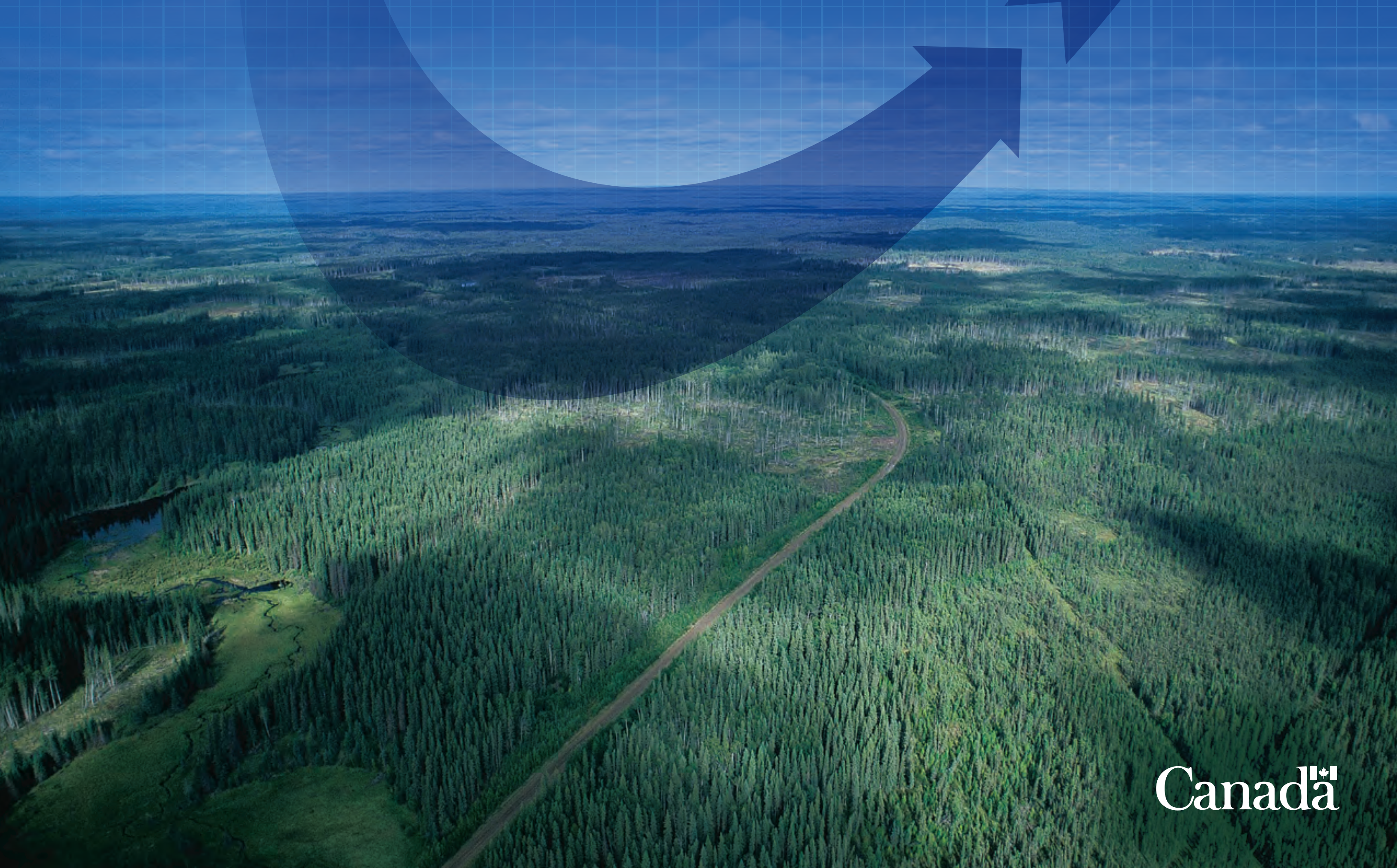
Natural Resources Canada | Ressources naturelles Canada

A Blueprint for Forest Carbon Science in Canada 2012–2020



Canada

A Blueprint for Forest Carbon Science in Canada 2012–2020

Coordinated and prepared by

Pierre Bernier, Werner A. Kurz,
Tony Lemprière, and Catherine Ste-Marie

Based on input from the Canadian
forest carbon science and policy communities

Cat. no. Fo4-43/2012E
ISBN 978-1-100-21266-1

Copies of this publication may be obtained free of charge from
Publications
Natural Resources Canada
c/o St. Joseph Communications
Order Processing Unit
1165 Kenaston Street
PO Box 9809 Station T
Ottawa, ON K1G 6S1
Telephone: 1-800-387-2000; Fax: 613-740-3114; TTY: 613-996-4397
E-mail: dlsorderdesk@eprintit.com

A pdf version of this publication is available through the Canadian Forest Service Publications database:
http://cfs.nrcan.gc.ca/publications

Cet ouvrage est publié en français sous le titre : *Plan d'action pour la science du carbone forestier au Canada : 2012–2020.*

Editing and production: Paula Irving
Design and layout: Sandra Bernier

Library and Archives Canada Cataloguing in Publication

A blueprint for forest carbon science in Canada: 2012–2020 / coordinated and prepared by Pierre Bernier ... [et al.].

Issued also in French under title: Plan d'action pour la science du carbone forestier au Canada : 2012–2020.
Includes bibliographical references.
Available also on the Internet.
ISBN 978-1-100-21266-1
Cat. no.: Fo4-43/2012E

1. Forests and forestry—Climatic factors—Canada.
2. Forest management—Environmental aspects—Government policy—Canada.
3. Greenhouse gas mitigation—Government policy—Canada.
4. Climate change mitigation—Government policy—Canada.
5. Plant-atmosphere relationships—Canada.
6. Plant biomass—Carbon content—Canada.
7. Environmental policy—Canada.
I. Bernier, Pierre, 1954- II. Canadian Forest Service

SD387 E58 B58 2012 333.750971 C2012-980181-X

Printed on recycled paper Printed in Canada Printed on alkaline permanent paper

CONTENTS

ACKNOWLEDGMENTS

We thank Mary Mes-Hartree and Darcie Booth for their comprehensive reviews and their support throughout the development of the Blueprint. We also thank Anna Dabros and Mark Hart for their diligent support. We acknowledge the significant financial support of the Canadian Forest Service. We especially acknowledge the forest carbon science and policy communities for their involvement and contributions without which this Blueprint would not have been possible. We greatly appreciate the rigorous work of English editor Paula Irving, graphic designer Sandra Bernier, and French editors Lucille Millette and Benoît Arsenault. All of those named above are with Natural Resources Canada, Canadian Forest Service.

EXECUTIVE SUMMARY

Domestic and international concerns about climate change have led to questions about the contemporary and future role of Canada's forests and forest sector in affecting atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs). In 2008, the Canadian Council of Forest Ministers described climate change, including adaptation and the role of forest carbon (C) in helping mitigate climate change, as one of two priorities of national importance facing the Canadian forest sector over the next decade.

Forest C policy needs to be informed by the best available scientific information. In the past few decades, scientific progress has been substantial and has contributed immensely to forest C policy, but considerable uncertainties remain and policy needs are evolving. This Blueprint outlines the priority forest C research activities needed in Canada to support policy until 2020. An understanding of policy-relevant research priorities will help funding organizations and the forest C science and policy communities in governments, universities, and the forest sector focus their resources and align their efforts. The forest C science and policy communities in Canada provided substantial input during the development of this document.

The needs of different stakeholders will vary depending on their particular circumstances, and so will the importance they attach to various science and policy issues and questions. This Blueprint discusses

+ the overarching forest C policy issues that are expected to be important for governments and the forest sector to 2020 (Table EX 1);
+ the forest C science questions, and the research priorities to address these questions, that are expected to be of greatest relevance for policy to 2020 (Table EX 1); and
+ the science approaches, infrastructure, and partnerships needed to make progress in addressing these research priorities.

Continued focused and coordinated efforts to address the key research goals by 2020 will be needed to maintain the successful record of Canadian forest C science. Ongoing investment in forest C science activities, expertise, and infrastructure will be needed, but estimation of investment levels and corresponding results are beyond the scope of this document. The speed and breadth of development of new knowledge and information, and their contribution to policy, will vary depending on the level of investment. This Blueprint proposes 11 actions that, if implemented and sustained to 2020, will help ensure that Canada's forest C science meets future policy requirements:

1. strengthen networking and knowledge exchange in the forest C science and policy communities;
2. develop frameworks for forest C data integration, synthesis, and analysis;
3. quantify the impacts of environmental drivers on forest C dynamics, with reduced uncertainty;
4. quantify the impacts of human activities on forest C dynamics, with reduced uncertainty;
5. expand forest C budget analyses to Canada's entire forest area;
6. improve spatial coverage, accuracy, and timeliness of forest inventory information;
7. generate in a timely manner annual statistics on areas affected by fires, insects and diseases, forest management, and land-use changes;
8. enable spatial and temporal extrapolation of C fluxes;
9. integrate forest C science into larger-scale assessments of C fluxes;
10. generate interdisciplinary assessments of the biophysical and economic implications of forest C mitigation options; and
11. train and develop the next generation of C science experts.

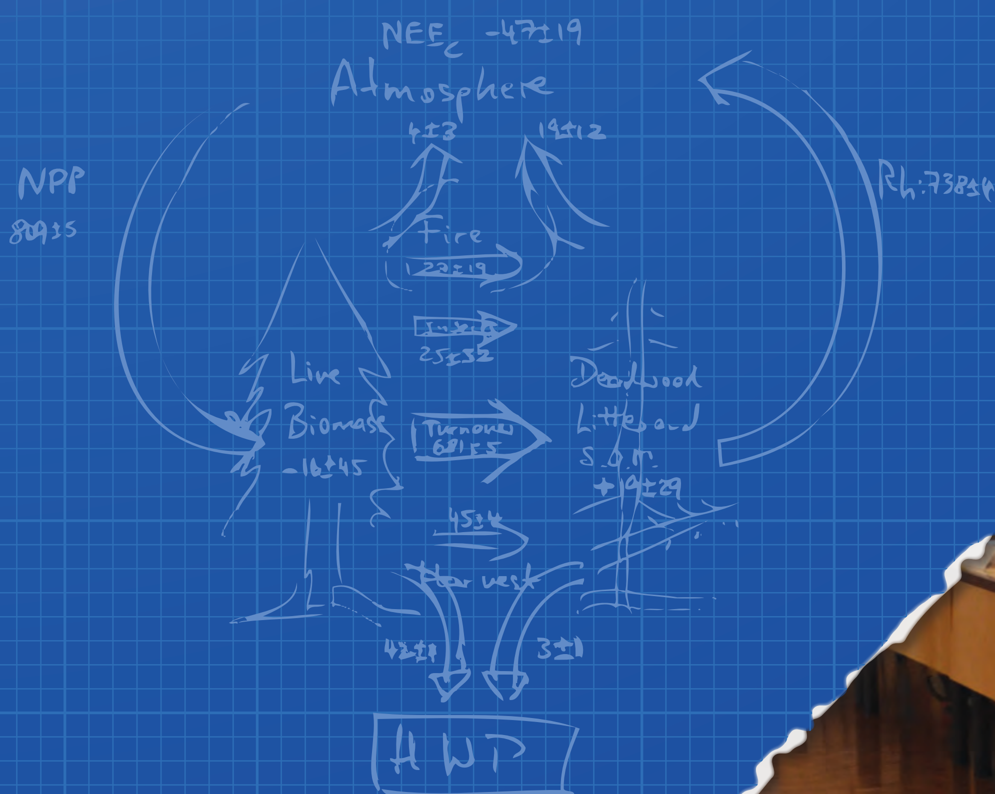
TABLE EX 1. Contribution of forest C science to forest C policy themes.

SCIENCE THEMES AND QUESTIONS	POLICY THEMES			
	1. Climate-responsible forest stewardship	2. Reporting requirements	3. Policies and rules that reflect Canada's forest characteristics	4. Climate change mitigation
1. Improved estimates of current GHG sources and sinks in Canada's forests 1.1. What are the impacts of natural disturbances, forest management, and land-use change on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales? 1.2. What are the impacts of climate variability, including drought, on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales? 1.3. How do local processes determining current forest C dynamics scale up to regional and national scales?	+	+	+	+
2. Improved estimates of the effects of global changes on Canada's future forest C 2.1. To what extent will global changes alter C sources and sinks in Canada's forests? 2.2. How will the impact of climate change on forest natural disturbances affect Canada's future forest C budget?	+		+	+
3. Improved estimates of the impact of Canada's forests on the global climate system 3.1. How does the influence of forest C fluxes on climate compare to the influence of other processes and properties related to forest cover? 3.2. What will be the contribution of Canada's forests to the future global GHG budget?	+			+
4. Improved estimates of the contribution that Canada's forests can make to climate change mitigation 4.1. What activities in forest ecosystems can best contribute to mitigation objectives? 4.2. What actions involving harvested wood products can best contribute to mitigation objectives? 4.3. What actions involving bioenergy from forest biomass can best contribute to mitigation objectives while ensuring the sustainability of biomass harvesting?	+		+	+

We hope that the Blueprint will be used as a guide for research and for the critically important tasks of coordination and integration of Canadian forest C science. The increasingly complex and evolving policy challenges of the 21st century require the support of well-integrated, coordinated, and sustained scientific research programs that are focused on answering policy questions. This Blueprint is meant to provide a foundation for this effort to increase the likelihood that the forest C policy challenges of the next decade are met successfully.

CHAPTER 1

Introduction



CHAPTER 1. INTRODUCTION

1.1 Purpose of the Blueprint

Forest carbon (C) has emerged as an important policy issue in the late 1990s and will remain important in coming years. Domestic and international concerns about increasing concentrations of CO_2 and other greenhouse gases (GHGs) in the atmosphere have led to questions about the contemporary and future role of Canada's forests and forest sector in affecting atmospheric GHG concentrations. Federal, provincial, and territorial governments have established GHG reduction targets for 2020 and beyond, and forests and forest sector activities could play a role in achieving those targets. Governments, forest sector companies, environmental groups, Aboriginal peoples, and others in Canada are interested in how forests can be managed, and forest biomass used, to maintain C storage, increase C removals, and reduce GHG emissions. This has added a new consideration to the policy and practice of sustainable forest management in Canada, one for which knowledge and understanding are still growing. In 2008, in *A vision for Canada's forests: 2008 and beyond*, the Canadian Council of Forest Ministers described climate change, including adaptation and the role of forest C in helping mitigate climate change, as one of the two priorities of national importance facing the Canadian forest sector over the next decade (CCFM 2008).

Good forest C policy needs to be based on the best available scientific understanding. Forest C science in Canada has already made important contributions to policy because of advances in the past few decades by government and academic researchers, as described below. The purpose of this document is to outline the research needed to ensure that these contributions continue as policy needs evolve and require increasingly sophisticated scientific understanding. The primary audience of this Blueprint is the forest C science community in federal, provincial, and territorial governments; universities; and elsewhere in Canada, including both researchers and science-funding organizations. The Blueprint will also be informative for the policy community in governments and for the broader forest sector. This document is neither a detailed work plan nor funding proposal but rather is an overview of the key forest C science research questions and priorities to 2020: progress in addressing these priorities will contribute directly to addressing policy issues and questions important to governments in Canada as well as to the broader forest sector. A sense of policy-relevant research priorities will help researchers, managers, and funding organizations focus their resources and align their efforts. This Blueprint discusses

+ the overarching forest C policy issues that are expected to be important for governments and the forest sector to 2020;
+ the forest C science questions, and the research priorities to address these questions, that are expected to provide the greatest support for policy to 2020; and
+ the science approaches, infrastructure, and partnerships needed to make progress in addressing these research priorities.

The overarching forest C policy issues and scientific research priorities in this Blueprint are based on input from science and policy experts in the federal, provincial, and territorial governments and academia. Three drafts of this document were circulated for comment, and several workshops and other focused discussions were held to identify key questions and research priorities. At each stage, all comments were taken fully into account to make this document as reflective as possible of the broad, diverse, and sometimes diverging views about what forest C science is most needed over the next decade. A summary of the process used to develop this document follows (see the box). Although views were sought across the range of scientific disciplines and research organizations involved in forest C science, the discussion in this document does not prejudge which organizations will or should undertake research.

Periodic review of this Blueprint will be important. A review every three to four years will ensure that the policy issues, science questions, and research priorities remain relevant.

Developing the Blueprint for Canadian Forest Carbon Science

The development of the Blueprint depended on the involvement of forest C scientists and policy analysts nationwide.

+ March 2010—At a workshop in Victoria, BC, 30 federal government participants delineated key forest C issues, considering both scientific and policy perspectives.
+ June 2010—A draft of the Blueprint generated from the workshop discussion was sent for a review to 93 academic and federal, provincial, and territorial government experts who provided about 900 comments.
+ January 2011—A substantially revised draft was sent for a second review to about 135 national and international experts who provided over 1000 comments.
+ March 2011—At a second workshop in Québec City, QC, 35 experts from governments and academic institutions helped further improve the Blueprint.
+ February 2012—A third draft was sent for final review to everyone who had contributed to the development of the Blueprint.

The input of the contributors (see Contributors at the end of the document) has ensured that the Blueprint comprehensively addresses the issue of forest C science and its relation to forest C policy in Canada. The Blueprint has benefited immeasurably from the contribution of these experts. Although it is not a consensus document, it is intended to faithfully reflect the broad range of input.

1.2 Context

Canada's forests are a renewable source of timber, bioenergy, and other goods and services. They constitute 10% of the world's forest cover and 30% of its boreal forest (Natural Resources Canada 2011a). Forest land covers 348 million ha or 40% of Canada's land area with another 42 million ha covered by other wooded land (Natural Resources Canada 2011a). Not all the forest land is managed: in 2009, the estimated managed forest area was 229 million ha, meaning that it was managed for timber and nontimber resources (including parks) or subject to fire protection (Environment Canada 2012).

The Canadian forest sector has made an enduring commitment to sustainable forest management defined as the maintenance and enhancement of the long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social, and cultural opportunities for present and future generations (Natural Resources Canada 2011b). Within this approach, the federal, provincial, and territorial governments each have a variety of policy goals related to forests in the context of their own jurisdictional responsibilities. Most of Canada's forest land is publicly owned and under provincial or territorial jurisdiction (77%) or federal jurisdiction (16%). The remaining forest land (7%) is privately owned (Natural Resources Canada 2011a). Provincial and territorial governments have legislative authority over conservation and management of their lands. In addition to managing some forest lands, the federal government has responsibility for the national economy, trade, and international relations, for which forests and the forest sector are important elements. The federal government also has responsibilities related to Aboriginal peoples whose communities are predominantly in forested areas. The forest industry has forest management responsibilities through legal arrangements with provincial governments. Private forest owners, whether they own small woodlots or are forestry companies with large holdings, often have their own management objectives. Underlying the interest of governments and others in the forest sector are the multifaceted economic, social, and environmental goals of sustainable forest management, ranging from government revenue, employment, rural community stability, market development and profit,

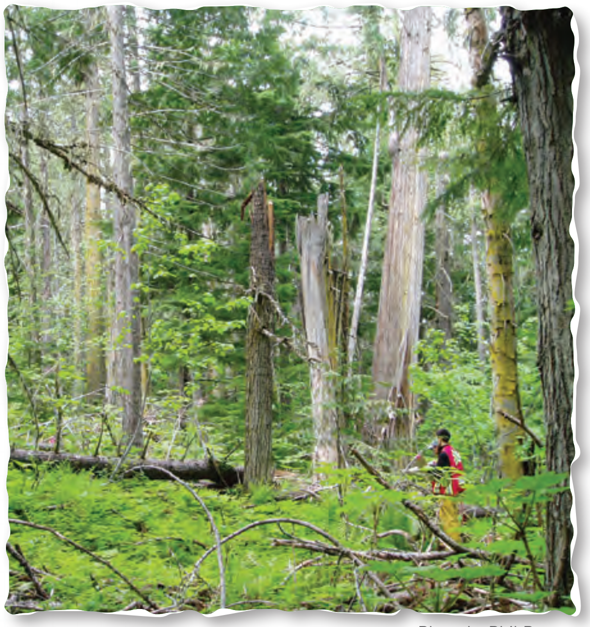


Photo by Phil Burton

to maintenance and conservation of ecosystems and the services they provide, one of which is C storage.

Forests interact dynamically with the atmosphere through massive exchanges of energy, C, and other gases that affect the earth's energy balance and climate. Since 1990, the world's forests have removed from the atmosphere about 30% of the global emissions of CO_2 due to fossil fuel combustion, cement production, and land-use change such as deforestation (Pan et al. 2011). Canada's forests are important in the global C cycle because of their size and because they contain vast quantities of C stored in vegetation, deep organic soil, and permafrost pools. Our forests can be C sinks or sources from year to year depending on the net balance of large fluxes between the atmosphere and the forest. On average, the managed forest was a small net sink of C from the atmosphere in 1990–2008 (see Figure 1). The net exchange with the atmosphere is the sum of C gains through net primary productivity (NPP, the net rate of C removal from the atmosphere as a result of photosynthesis and plant respiration), C emissions through decomposition of dead organic matter (heterotrophic respiration), and C emissions during fire (which also results in emissions of methane and nitrous oxide). Large transfers of C from live biomass to dead organic matter occur in the forest as a result of annual turnover, fires, insect-induced mortality, and harvesting (see Figure 1). The C stocks of forest stands often are characterized by long periods of slow C uptake punctuated by relatively short periods of large C losses due to harvesting, fire, severe insect disturbances, or other severe natural disturbances. At the landscape level, increased natural disturbance regimes (wildfires and insect infestations), influenced by climate change, have recently caused the managed forest C stock to decline in parts of Canada and for the country as a whole (Environment Canada 2012; Stinson et al. 2011). In addition to emissions of C to the atmosphere, C is lost from the forest through transfers of dissolved organic C to aquatic systems, and through harvesting. Emissions from harvested wood products occur over time depending on the type of product (e.g., lumber, paper, bioenergy) and how it is used. As well, there are indirect substitution effects because the use of wood can reduce fossil fuel GHG emissions when it replaces more emissions-intensive materials such as concrete and steel, or when it replaces fossil fuels.

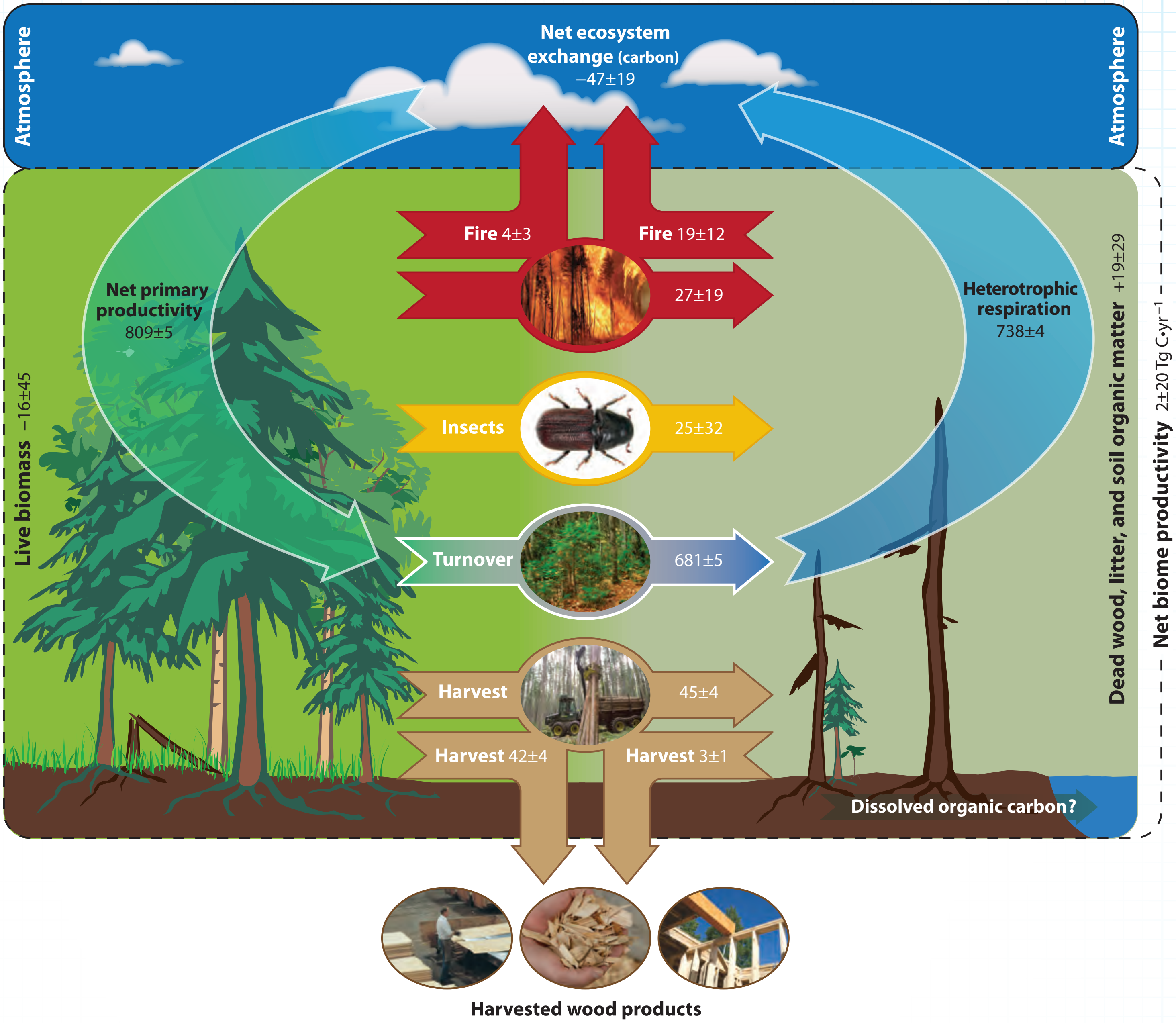


FIGURE 1. Estimated C balance of Canada's managed forest for 1990–2008, Tg (Mt) C•yr^{-1}. The numbers show the annual mean ± one standard deviation based on 19 annual values. The small net forest C uptake from the atmosphere (negative net ecosystem exchange of carbon, NEE_C) is the difference between two large fluxes (net primary productivity and heterotrophic respiration) plus emissions from fires. Only a fraction of the forest C uptake was estimated to have accumulated in the forest (positive net biome productivity, NBP) in the period. (Stinson et al. 2011.)

It is increasingly recognized that feedbacks between climate and long-lasting terrestrial C pools may profoundly alter the trajectory of future atmospheric GHG concentrations and climate change (e.g., Metsaranta et al. 2011). This means that the outcomes of global efforts to stabilize atmospheric GHG concentrations by reducing net GHG emissions could be strongly affected by the response of land ecosystems to climate change. As a result of fire and insect disturbances, interannual variability in the net GHG balance of Canada's managed forest has been estimated to already be equivalent to about 50% of Canada's total anthropogenic GHG emissions (Environment Canada 2012). Increased emissions from our forests due to future climate change impacts, including changes in fire regimes, decomposition rates, tree mortality rates, and other processes, are highly uncertain but could be large (Metsaranta et al. 2010) and even


Photo by Ruth Errington

exceed emission reductions achieved in all other sectors. Moreover, the direction and magnitude of forest feedbacks to the C cycle as a result of climate change, the existence of tipping points at which ecological processes irreversibly change from one state to another, and the rates of future changes, are still not well understood (IPCC 2007a). Because of feedback effects, the question of how Canada's forest C budget will respond to global climate change has scientific, environmental, and policy relevance, not just for future mitigation efforts but also for adaptation.

Canada's forest C science is internationally recognized. Research already has substantially advanced the understanding of the current and anticipated C sinks and sources in Canada's forests, the processes that influence them, and the contribution of the managed forest to the global C cycle. Progress has also been made in understanding the range of mitigation options to reduce GHG emissions and increase C sequestration in forest ecosystems and the forest sector. Tools have been developed to help forest managers in provincial and territorial governments and industry assess the implications of human activities on the forest C cycle. Based on many years of cooperation between federal, provincial, and territorial governments, estimates of historical C stock changes and GHG emissions associated with the managed forest and land-use change are now produced annually for national reporting by the federal government, with provincial estimates published by some provinces. Forecasts of future C stock changes and GHG emissions taking into account the impacts of natural disturbance regimes have been developed for a variety of purposes.

Although progress has been substantial, considerable uncertainties remain and addressing those uncertainties is the focus of this Blueprint. Policy makers and forest managers now face the challenge of folding C and GHG considerations into sustainable forest management, and balancing those considerations with other forest management goals. They face the challenge of determining how forests and forest C can best contribute to achieving GHG emission reduction targets. They will continue to rely on the forest C science community to provide the information and knowledge necessary for sound decisions and to report on how forest-related C and GHG emissions in Canada are changing, and why.

1.3 Scope of the Blueprint

The focus of this Blueprint is research on the C pools in managed and unmanaged forest ecosystems in Canada: above- and belowground biomass, dead wood, litter, and soil. It also covers research on forested peatlands, and the interface between forest and aquatic ecosystems such as wetlands. The scope includes policy-relevant C science related to both forest ecosystems and the forest sector. It therefore covers issues related to the fate of C in harvested wood products and the implications of substituting wood for fossil fuels and more emissions-intensive building materials.

Although the focus is on C stocks and their changes, climate-relevant non-CO_2 GHGs such as methane and nitrous oxide, which are included in domestic and international GHG reporting and policy, are covered. In this report, C refers to CO_2 and these other GHGs, as appropriate, and references to emissions refer to the net balance of emissions and removals. Other climate-relevant characteristics of forest ecosystems, such as albedo (the fraction of solar radiation reflected by surfaces on the earth), are also considered.

Options to manage forest C to contribute to climate change mitigation are addressed from biophysical and economic perspectives. Policy decisions around C management will need to consider many other goals of sustainable forest management, such as those related to climate change adaptation, biodiversity, water resources, and employment, but the focus of this Blueprint is foremost on C issues. Adaptation to climate change and the sustainability of current forest management practices in light of climate change are important policy issues but are outside the scope of this Blueprint. Nevertheless, although this Blueprint does not directly address adaptation issues, clearly much of the research needed to better understand the impacts of a changing climate and adaptation strategies on forests is also needed to better predict the future impacts on C (e.g., research on the effects of climate change on forest dynamics and natural disturbances). And, as two complementary responses to climate change, adaptation and mitigation will increasingly need to be considered together, seeking synergies or minimizing trade-offs between the responses.

1.4 Structure of This Document

This document consists of four chapters, including this introductory chapter. Chapter 2 first describes the four overarching policy themes that will be the major drivers for forest C science research through to 2020. It then identifies four high-level forest C science themes and discusses their relevance to policy. For each science theme, a set of questions and key research goals to 2020 are described. Chapter 3 comments on methodological, technological, infrastructural, and institutional developments that will help ensure these goals are addressed effectively. Chapter 4, the conclusion, proposes actions to implement the Blueprint and presents an initial vision of an integrating system for forest C science in Canada.

CHAPTER 2

Forest Carbon Science and Policy Needs

Nordic Engineered Wood

CHAPTER 2. FOREST CARBON SCIENCE AND POLICY NEEDS

2.1 Policy Themes

The growing interest in the role of forest C in regulating climate and mitigating climate change has added new dimensions and goals to policy discussions about forests in Canada. Specific policy goals for forest C in the period to 2020 will vary across jurisdictions and organizations and evolve over time, and it is beyond the scope of this Blueprint to discuss each specific goal. Instead, this Blueprint assumes that the forest C policy interests of the federal, provincial, and territorial governments and others can be encapsulated within four broad interrelated and overlapping policy themes. These themes are not new, but they have become increasingly important over the last decade and forest C science has already contributed to each one.

Policy Theme 1. Climate-responsible forest stewardship

Canadians and the international community expect responsible stewardship of Canada's forests, ensuring a sustainable flow of goods and services and taking into account climate-driven changes. As understanding and concerns about forest C and climate change increase, so too does the expectation of climate-responsible forest stewardship. This relatively new aspect of stewardship requires integration of understanding about climate change adaptation, forest C, and GHG emissions, and climate change mitigation (see Policy Theme 4) in sustainable forest management objectives, planning, and practices. The generation and application of scientific knowledge about how management and land-use change affect forest C, and about how C-related goals and other goals of sustainable forest management can be balanced, are fundamental for this integration. The ability to achieve and demonstrate successful integration has implications for access to markets for Canadian forest products.

Climate-responsible forest stewardship must be carried out and demonstrated in an increasingly globalized environment in which interest, concern, and information about our forests exist throughout the country and far beyond our borders, with potential economic consequences. For example, scientific organizations, foreign countries, and environmental nongovernmental organizations increasingly monitor, attempt to verify, and in some cases challenge statements and information about forest stewardship in Canada, including estimates of forest C budgets. Governments in Canada want to ensure that sound science-based information and knowledge about forests and forest C, and how they are managed, are available at home and abroad. As well, research and monitoring programs operated abroad need to benefit from Canadian collaboration and input to ensure that our forests are appropriately represented and to enhance the international understanding of the characteristics of our forests and forest management. Demonstrating responsible stewardship also means providing information about the role of Canada's forests in the global C cycle and climate system now and in the future.

Climate-responsible forest stewardship is not just about ensuring and demonstrating sound stewardship in Canada but also about helping other countries achieve comparable stewardship. For example, Canada can assist other countries in developing their forest C monitoring and management systems to improve their reporting capabilities and contribute to climate change mitigation. Doing so can support Canadian forest-related international policy objectives such as establishing common standards for sustainable forest management and reducing GHG emissions from deforestation and forest degradation in developing countries.

Policy Theme 2. Domestic and international reporting requirements

Canadians and the international community expect Canada to monitor and report on the state of its forests, including its forest C. On behalf of Canada, the federal government must annually estimate and report C stock changes and GHG emissions in the managed forest, from harvested wood products and from land-use change involving forests (afforestation, deforestation) as part of annual GHG inventory reporting required by the United Nations Framework

Convention on Climate Change (UNFCCC). Additional reporting requirements could be established as part of future international climate change agreements reached under the UNFCCC. The federal government also periodically reports Canada's forest C stocks and stock changes in all forest lands (both managed and unmanaged) to the Food and Agriculture Organization of the United Nations.

Domestically, reporting is required for a variety of reasons: for provincial/territorial GHG inventory reporting (provinces such as British Columbia and Ontario undertake their own reporting on forest C stock changes and GHG emissions); for national and provincial/territorial State of the Forest reports; for monitoring of criteria and indicators of sustainable forest management; and for helping forest management organizations meet their sustainable forest management certification requirements. Consistent reporting through these various means contributes to the demonstration of climate-responsible stewardship that supports continued access to forest product markets (see Policy Theme 1).

Estimates and reporting of anthropogenic forest C stock changes and GHG emissions over time are needed by governments and others for assessing the impact of human activity on forest and harvested wood product C, for assessing progress in reducing GHG emissions and increasing C sequestration, and for understanding the anthropogenic contribution to observed increases in atmospheric GHG concentrations. Federal, provincial, and territorial governments have already made important progress in working together to regularly develop and provide estimates related to forest C and GHGs to meet international, national, and provincial/territorial reporting requirements. To remain the source of authoritative information on C in forests and forest products, Canadian jurisdictions need to continue to regularly report transparent, verifiable, science-based estimates. Moreover, they need to continuously improve the reported estimates to strengthen and refine their usefulness for policy, especially by improving estimates of anthropogenic emissions (see Policy Theme 3). As well, internationally, reporting guidelines under the UNFCCC specify that uncertainties in estimates provided by Canada must be continuously identified, quantified, and reduced as far as practicable (IPCC 2006). Scientific research over the next decade is required for all these tasks.

Policy Theme 3. Policies and rules that reflect Canada's forest characteristics

International and domestic discussions on forest C need to reflect the unique nature of Canada's forests, and result in policies or rules that make sense given the characteristics of its forests and forest management. Canada has a continental-scale forest, only a relatively short history of forest management, and a low human population density. Most of the country's forests are relatively old and slow growing. Forest rejuvenation occurs through large and ecologically important stand-replacing natural disturbances, with forest management activities now contributing to this process. These properties have significant effects on C dynamics, and also favor extensive rather than intensive forest management.

Forest C science has informed the development of voluntary C offset protocols and projects as well as provincial and territorial policy discussions about how to include forests in C offset trading systems. A framework for forest management offset quantification protocols has been developed by the Canadian Council of Forest Ministers (CCFM 2009), and quantification protocols are being developed and implemented by some provinces. As offset systems are further developed and implemented, additional scientific input will be needed on issues such as setting offset project baselines and defining and quantifying the impacts of project activities on C and GHGs.

Forest C science has also effectively informed Canada's position in international climate change negotiations in the last 15 years under the UNFCCC: the need for science-based advice and analysis will be ongoing and evolving as international discussions continue over the next decade. A key issue for policy both domestically and internationally, and hence for scientific research, is separating the direct human influence on forest C stock changes and GHG emissions (due to forest management and land-use change) from natural effects (e.g., due to natural disturbances) and indirect human effects (e.g., due to anthropogenic climate change). The magnitude of natural disturbance impacts on forest C across Canada means that the impact of direct human activity is difficult to quantify, yet it is the direct human activity that is the focus of policies and rules. The ability to monitor and evaluate the effect of policy is very important, and therefore the ability to assess the direct human influence is also very important.

Policy Theme 4. Climate change mitigation

The federal, provincial, and territorial governments have established GHG reduction goals aimed at mitigating climate change. Reducing GHG emissions requires that society make progress in decoupling economic activity and growth from emissions, implying an emphasis on clean energy sources, increased efficiency in the use of resources, and clean technologies. Also, governments and others are interested in how forests and forest biomass can contribute to mitigation efforts. They want to know the mitigation strategies and forest management practices that will increase C sequestration or reduce emissions, by how much and at what cost, and they want to know how these strategies relate to other forest management goals and climate change adaptation.

Globally, it is recognized that forests have substantial mitigation potential (IPCC 2007b). Our understanding of the forest-related mitigation potential in Canada has increased substantially over the past 15 years, but our knowledge is still fragmented, reflecting the diversity of ecological conditions and management practices. Many activities involving forest C may be able to contribute to mitigation objectives, but net mitigation benefits, timing, and costs can differ greatly among mitigation options. Policy choices and strategic and operational decisions about which activities to implement will need to incorporate environmental, economic, and social dimensions, including the relationship with goals and strategies for climate change adaptation. Making progress on understanding and implementing mitigation options requires science-based guidance, information, and tools for decision makers at all levels, including provincial/territorial forestry agencies, forest sector companies, private forest land managers, and users of wood products and bioenergy. Much of this scientific support will also inform evaluation and decision making about adaptation options.

2.2 Science Themes, Questions, and Key Research Goals

C science needs to provide knowledge and tools to support the four policy themes described previously. Table 1 lists the four high-level interacting science themes that are the focus of this Blueprint, and shows how they relate to the policy themes. These science themes are neither new nor static: they are paths along which scientific advances are needed to meet policy demands for information in an evolving policy and science environment and in a changing climate.

Several specific questions with associated key research goals are identified for each of the science themes. The key research goals address the improvements in understanding and information over the next decade that will most directly help answer the science questions and satisfy information needs of federal, provincial, and territorial policy makers. The goals are determined based on the current understanding of the processes driving forest GHG emissions and removals, sources of uncertainty, knowledge gaps, and vulnerability of processes to changes in environmental conditions. This section describes only the science questions and goals: chapter 3 discusses scientific approaches, infrastructure, and institutional arrangements for answering these questions.

Science Theme 1. Improved estimates of current GHG sources and sinks in Canada's forests

This science theme is relevant to each of the four policy themes, and relates to science activities aimed at quantifying the spatial and temporal distribution of contemporary sources and sinks of GHG in forests, the processes that govern these fluxes and their relative importance, and the uncertainty of these estimates. This knowledge provides the scientific foundation needed to predict C cycle responses to climate change, as well as the evaluation of actual and potential forest-related GHG emissions and C sequestration relative to those in other sectors in Canada.

The factors that determine the spatial and temporal distribution of C sources and sinks in Canada's forests are (1) the spatial and temporal distribution of natural and anthropogenic disturbances, (2) the responses of ecosystems to natural environmental conditions and their variability, and (3) the responses of ecosystems to long-term human-induced changes in these environmental conditions, including climate

TABLE 1. Contribution of forest C science to forest C policy themes.

SCIENCE THEMES AND QUESTIONS	POLICY THEMES			
	1. Climate-responsible forest stewardship	2. Reporting requirements	3. Policies and rules that reflect Canada's forest characteristics	4. Climate change mitigation
1. Improved estimates of current GHG sources and sinks in Canada's forests 1.1. What are the impacts of natural disturbances, forest management, and land-use change on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales? 1.2. What are the impacts of climate variability, including drought, on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales? 1.3. How do local processes determining current forest C dynamics scale up to regional and national scales?	+	+	+	+
2. Improved estimates of the effects of global changes on Canada's future forest C 2.1. To what extent will global changes alter C sources and sinks in Canada's forests? 2.2. How will the impact of climate change on forest natural disturbances affect Canada's future forest C budget?	+		+	+
3. Improved estimates of the impact of Canada's forests on the global climate system 3.1. How does the influence of forest C fluxes on climate compare to the influence of other processes and properties related to forest cover? 3.2. What will be the contribution of Canada's forests to the future global GHG budget?	+			+
4. Improved estimates of the contribution that Canada's forests can make to climate change mitigation 4.1. What activities in forest ecosystems can best contribute to mitigation objectives? 4.2. What actions involving harvested wood products can best contribute to mitigation objectives? 4.3. What actions involving bioenergy from forest biomass can best contribute to mitigation objectives while ensuring the sustainability of biomass harvesting?	+		+	+

and atmospheric CO_2 concentrations. Quantifying the magnitude and direction of responses in GHG fluxes in the first two groups of processes and the integration of this information over space and time are prerequisites to addressing Science Theme 1.

The third group of processes—long-term trends in human-induced environmental changes—is likely already affecting the forest C balance, but its impacts are most pertinent to Science Theme 2.

Science Question 1.1 What are the impacts of natural disturbances, forest management, and land-use change on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales?

To assess the net C exchange of forests with the atmosphere at various spatial and temporal scales, we need to quantify (a) the frequency and extent of natural disturbances (e.g., fire, insects, diseases, windthrow, ice storms) of forest management (e.g., harvesting, salvage logging, controlled burning, suppression of natural disturbances), and of land-use change (deforestation, afforestation); (b) the rate of recovery of disturbed forests; and (c) the impacts on stand-level C dynamics. At regional scales, natural disturbances and forest management impose long-term dynamics on the forest C balance by affecting forest age-class structure; forest species composition, growth, mortality, decomposition, and dead organic matter; and soil C dynamics. Research to quantify impacts of disturbance on forest C dynamics is ongoing, with a focus on the managed forest. Because both the managed and unmanaged forest are relevant to understanding the role of Canada's forests in the global C cycle and climate, information on the unmanaged forest is also needed. Note that understanding the climate change mitigation potential of changes in forest management and land-use change is the focus of Science Theme 4. Key research goals that follow identify areas where continued research and improvements most directly help answer Science Question 1.1.

Key Research Goals

- G1 Linking annual high-resolution maps of burned areas in Canada's managed and unmanaged forest to improved estimates of fire severity and carbon losses.
- G2 Finer spatial resolution of estimates of area and severity of annual infestations by major forest pests.
- G3 Estimates of direct fire GHG emissions and postfire C dynamics, including postfire site development, for diverse forest types, particularly nonboreal forests, forested peatlands, and other areas with deep organic soils.
- G4 Estimates of infestation impacts of major forest pests on site C dynamics, including ecological recovery, for a broad range of impact types, severity, and pre-attack stand properties.
- G5 Estimates of the extent and severity of locally relevant extreme weather events such as ice storms and wind throws and their impacts on forest C dynamics.
- G6 Estimates of the extent and impacts on stand and landscape C dynamics of all forest management practices and land-use changes, including afforestation and deforestation.
- G7 Characterization and estimate of the interactions between multiple disturbances (e.g., fire, insects, pathogens, forest management), and the impact of these interactions on C dynamics.

Science Question 1.2 What are the impacts of climate variability, including drought, on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales?

Climate variability is a secondary driver of the forest C cycle. Excluding fire, the small net C exchange of forests with the atmosphere is the difference between two large fluxes: uptake of C though photosynthesis and loss through respiration of trees and of decomposers (Figure 1). Climate-related events such as variations in spring temperature and multiyear drought can affect these two large and opposite fluxes through changes in ecosystem processes, and cause significant interannual variability in the net C balance of forests. Although processes are affected at the levels of trees and stands, the synchronicity of climate events over large areas can generate effects on regional, national, and even hemispherical-scale C fluxes. The key research goals that follow relate to areas where research is ongoing but where increased efforts are needed to improve the quantification of C dynamics at large temporal and spatial scales.

Key Research Goals

- G8 Quantification of stand-level relationships between current climate variability, stand history, and C flux for major forest ecosystems and disturbance types, over temporal scales from days to decades.
- G9 Reconstruction and quantification of relationships between past climate variability and forest growth, over temporal scales from years to centuries.
- G10 Quantification of extent and importance of impacts of annual to decadal climate variability, including drought, on ecosystem productivity and C fluxes, and of the uncertainties associated with these estimates.

G11 Integration of information on forest responses to climate variability from different sources in process models of forest C dynamics, including quantification of uncertainties.

Science Question 1.3 How do local processes determining current forest C dynamics scale up to regional and national scales?

An understanding of current forest C dynamics at the regional and national scales is necessarily built from information integrated across relevant processes and scales. Integration of local information up to regional and national scales requires models within which forest data, disturbance information, and process simulation can be combined in a manner that accounts for their inherent differences in scale of representation. Existing process models can estimate the impacts of environmental variability on C dynamics and some of these models have the capacity to represent the impacts of natural disturbances, forest management, and land-use changes at regional to national scales. But challenges still remain with the validation of their results. Existing inventory-based models capture the effects of disturbance and land-use change but not interannual climatic variability or climate change. Top-down estimates use data assimilation and inverse modeling methodologies in which high-precision measurements of atmospheric CO_2 concentrations are combined with wind data and geographically explicit information on CO_2 emissions from point sources and CO_2 exchanges from major land cover types to map and quantify C source and sink dynamics at continental scales. These systems are becoming more sophisticated and efforts are under way to improve the spatial and temporal resolution of their estimates, better characterize (and reduce) their uncertainties, perhaps eventually operate in near real time. Forest C science contributes key information to these top-down estimates by providing emission estimates for forests and forest disturbances. However, the top-down approach requires that bottom-up estimates of forest C fluxes be expanded to national and continental scales. The key research goals provide direct support to the scaling of information on local C dynamics to regional and national scales.

Key Research Goals

G12 Accurate representation of the C dynamics of representative forest and disturbance types in process models and of the C dynamics related to

Photo by Mike Michaelian

climatic and global change forcings in inventory-based models.

G13 Improvement of bottom-up and top-down modeling results for Canada, using process-based bottom-up, inventory-based bottom-up, and top-down approaches to provide mutual constraints.

Science Theme 2. Improved estimates of the effects of global changes on Canada's future forest C

Global changes include changes in climate (temperature and precipitation regimes) as well as other environmental changes such as increases in atmospheric CO_2, nitrogen deposition, and tropospheric ozone. This theme underscores the importance of research on predicting changes in forest GHG sources and sinks in response to these global changes, and on the quantification of the uncertainties in these predictions. The results will be relevant for forest management planning and will provide better estimates of the contribution of Canada's forests to the global C cycle in the future (Policy Theme 1). The improved inclusion of global change impacts on future forest C budgets will increase the robustness of domestic and international policy development (Policy Theme 3), including that related to mitigation choices (Policy Theme 4). The priorities are those for which work is most needed to improve the quantification of future forest dynamics (growth and mortality, disturbances, decomposition) and to improve the predictions of impacts on the net balance of C sources and sinks. The main focus is on the events and processes that are expected to have a large impact on the future forest C stock. Note that the key research goals listed for Science Theme 1 will contribute to this theme.

Science Question 2.1 To what extent will global changes alter C sources and sinks in Canada's forests?

Empirical models used in forest management assume that yield tables developed from historical data correctly represent present and future productivity. However, recent and predicted trends in atmospheric CO_2 concentrations, temperature, precipitation, and air pollutants have already imposed directional deviations from past averages and these deviations are likely to increase. Predicting Canada's future C sources and sinks requires quantification of the impacts of these global changes relative to those of other processes such as disturbances and climate variability. In addition, nonlinear responses that are beyond the range of historical observations could lead to dramatic changes in ecosystem C fluxes or irreversible changes in ecosystem characteristics (tipping points). For example, state changes such as creation of lichen woodlands when forest regeneration fails, or permafrost thaw and release of CO_2 and CH_4 in boreal forest ecosystems, are among processes susceptible to irreversible changes with potentially significant effects on future C fluxes.

Key Research Goals

G14 Determination of how, where, and to what extent observed changes in climate and in atmospheric concentrations of CO_2 and air pollutants have already altered forest C dynamics.

G15 Determination of how, where, and to what extent predicted changes in climate and in atmospheric concentrations of CO_2 and air pollutants could alter future forest C dynamics.

G16 Identification of conditions conducive to the generation of tipping points within forest ecosystems, including in soils, forest–prairie ecotone, forested peatlands, and permafrost, and prediction of locations where they are most likely to happen and their potential impact on GHG emissions and removals.

Science Question 2.2 How will the impact of climate change on forest natural disturbances affect Canada's future forest C budget?

Changes in natural disturbance regimes include changes in the timing, frequency, type, area affected (i.e., size), location, and severity of disturbances. Larger and more intense fires, longer fire seasons, range expansion of pests, and arrival of invasive alien insects or pathogens are likely to be among the most notable changes, though they will vary across the country. These changes will affect forest dynamics, age-class distributions, species composition, succession and regeneration, and consequently forest C stocks, and fluxes. Knowledge of past and current disturbance regimes forms the scientific foundation needed to address this question.

Key Research Goals

G17 Quantification of the long-term variability in past disturbance regimes.

G18 Characterization of climate change impacts on future disturbance regimes.

G19 Quantification of the potential impacts of climate change-altered disturbance regimes on landscape-level C dynamics.

Science Theme 3. Improved estimates of the impact of Canada's forests on the global climate system

Although anthropogenic CO_2 emissions to the atmosphere have more than doubled over the past 50 years, a nearly constant 45% of these emissions have been recaptured by terrestrial and marine ecosystems. This observation underscores both the world's dependency on natural sinks to offset some of the anthropogenic emissions and the need to improve predictions of the future contribution of terrestrial and marine sinks and the potential saturation of these sinks to better predict future atmospheric GHG concentrations and the resulting impacts on global climate. Moreover, forests contribute to the global climate system not only through their C cycle but also through the exchanges of water and energy with the atmosphere; changes in stand age and land cover could amplify or reduce GHG-induced climate impacts through changes in albedo, evapotranspiration, and other processes.

The size of Canada's forests (managed and unmanaged), in which large C fluxes are controlled by climate-regulated natural disturbances, means that they are an important component of the global climate system. One concern is that responses of our forests to a changing climate could trigger positive feedbacks as increased forest GHG emissions or reduced removals accelerate the increase of atmospheric GHG concentrations, leading to more climate change (i.e., the warming feeds the warming). Thus one important area of research under this science theme is an effort to describe the nature and magnitude of feedbacks, their ability to enhance or mitigate climate change, their rates of change, and the possibility that they may lead to tipping points. Another important area is research on how forest cover and changes in it affect climate through other non-C processes. All this research provides information on how Canada's forests will affect global climate in the future, supporting one aspect of Canada's climate-responsible forest stewardship (Policy Theme 1). It can also inform decisions about forest-based climate change mitigation (Policy Theme 4). C dynamics and GHG emissions in Canada's managed forests are better quantified than those in unmanaged forests: improving

our knowledge on unmanaged forests is therefore particularly important in this science theme because it is the whole forest that affects the global climate system. Key research goals specified under Science Themes 1 and 2 are relevant here in addition to those that follow.

Science Question 3.1 How does the influence of forest C fluxes on climate compare to the influence of other processes and properties related to forest cover?

Although the current focus of forest-climate feedbacks has primarily been on GHG-related processes, there is increasing realization that changes in albedo and evapotranspiration that result from changes in forest cover can also have important effects on the climate system. For example, changes in forest cover cause changes in both C fluxes and albedo, but the effect of albedo changes on radiative forcing of the climate is generally opposite in direction to the effect of C flux changes, and it can be large. Quantification of these processes could have important implications for decisions about which forest-related mitigation options to pursue.

Key Research Goal

G20 Characterization and quantification of changes in non-GHG radiative forcing and in the evaporative fraction as a result of forest management, natural disturbances, and land-use change that affect forest cover properties.

Science Question 3.2 What will be the contribution of Canada's forests to the future global GHG budget?

All modeling approaches can be used to model the past and present. However, unlike top-down and inventory-based models that are driven by observations and lack a predictive capacity, process-based models are capable of projecting into the future and are therefore critical components of climate models or

of fully coupled Earth-system models. Observational and manipulative studies enhance forest ecosystems processes understanding and modeling. This science question requires cooperation of the forest C-cycle measurement community with the atmospheric climate modeling community, and involvement in regional and global efforts to synthesize C cycle and climate predictions. Such collaborative work can improve the predictive capacity of global climate and C cycle models by ensuring better representation in the models of both the expected effects of climate change on forests and the potential feedback mechanisms between forests and climate change.

Key Research Goals

- G21 Characterization and quantification of forest-climate feedback mechanisms involving GHGs, including identification of C sinks at risk of disappearing, and their representation in climate models.
- G22 Scaling up of regionally based process-models in a manner that allows an improved representation of Canada's forest C dynamics in global coupled climate models.

Science Theme 4. Improved estimates of the contribution that Canada's forests can make to climate change mitigation

Climate change mitigation requires an understanding of how changes in activities relative to a baseline can reduce GHG emissions or increase C sequestration. Mitigation efforts involving forests and forest biomass can be aimed at reducing GHG emissions from the forest, maintaining or increasing C stocks in the forest or in harvested wood products, or reducing emissions through the use of these products instead of more emissions-intensive materials such as steel, concrete, plastics, or fossil fuels (substitution effects). Adding climate change mitigation as an objective under the overarching goal of sustainable forest management raises questions about trade-offs between mitigation, timber production, and other forest goods and services, and heightens the interest in the C implications of how we use harvested biomass. Economic assessment of mitigation is important because it helps in understanding the trade-offs and in comparing forest-related mitigation options with options in other sectors. Research in all these areas is relevant for policy making, strategic management planning, operational decision making, and certification systems. The key research goals are those for which work is most needed over the next decade to understand how Canada's forests and forest biomass can help mitigate climate change in the context of sustainable forest management (Policy Themes 1 and 4) and ensure that domestic and international policy development reflect Canada's potential and limitations in this area (Policy Theme 3).

Science Question 4.1 What activities in forest ecosystems can best contribute to mitigation objectives?

Mitigation activities in forests can include a broad range of sometimes conflicting options, and their true impacts can only be quantified through complete life-cycle analysis. Mitigation strategies could involve land-use changes such as afforestation and the reduction of deforestation, or reduction of the emissions from deforestation when it occurs. They could also include changes in forest management practices to increase stand-level or landscape-level C density. Other possible measures include changes in forest peatland management and efforts to reduce fire and insect disturbances. Where increases in forest C stocks involve reductions in harvest rates, there will be reductions in C storage in harvested wood products and in substitution benefits. Some of the forest-based mitigation options will take years to yield significant increases in forest C and this raises the issue of balancing actions that have long-term mitigation benefits with actions that contribute to more immediate goals for reducing GHG emissions. The development of cost-effective mitigation portfolios across sectors requires an understanding of the costs per tonne of GHG abatement activities in each sector.

Key Research Goals

- G23 Quantification of provincial/territorial and ecosystem-specific forest management options to increase forest C stocks over different time frames, including analysis of their relationship to the economy and other objectives of sustainable forest management.

G24 Quantification of the mitigation potential of land-use change options (e.g., reductions in deforestation rates, increased afforestation) at the landscape and provincial/territorial level, including economic analysis.

G25 Quantification of the mitigation potential of natural disturbance management options, in particular fire suppression, including economic analysis.

Science Question 4.2 What actions involving harvested wood products can best contribute to mitigation objectives?

Harvested wood products store significant amounts of C that is emitted over time as they are used and discarded. To address the timing and quantity of the emissions, mitigation efforts can address the choices about what products are produced, how they are used, and what happens when they are discarded, for example, recycling, burning, or depositing in landfills. Mitigation efforts can also focus on substitution for more emissions-intensive products. Life-cycle analyses are required to provide baseline information on these substitution options and the associated costs and benefits.

Key Research Goals

G26 Quantification of the emissions of C from harvested wood products produced in Canada and used domestically and in export markets based on detailed information on product types, their uses, and what happens when they are discarded.

G27 Quantification of the life-cycle mitigation potential of options to increase the longevity of harvested wood products, increase their substitution benefits, and reduce the emissions associated with their use and disposal, including economic analysis.

Photo by Julie Piché

Science Question 4.3 What actions involving bioenergy from forest biomass can best contribute to mitigation objectives while ensuring the sustainability of biomass harvesting?

Interest in forest biomass as a source of energy is growing. The mitigation potential of bioenergy depends on the C dynamics associated with the source of the biomass itself; the C emissions from its harvest, transport, and processing; the technological pathway for energy generation; and the avoided emissions from the energy source that bioenergy replaces. Bioenergy projects could generate economic and societal benefits in addition to GHG reductions, but such projects must be supported by sound scientific knowledge on issues ranging from the sustainability of biomass harvesting to analysis of their full life-cycle implications. Understanding the timelines of C costs and benefits of bioenergy projects is particularly important as some bioenergy supply options will not result in net reductions in GHG emissions for years or decades to come.

Key Research Goals

G28 Quantification of the implications for GHG emissions of increased use of wood bioenergy compared to appropriate baselines, as a function of biomass type, forest recovery, bioenergy technology choices, and energy sources that bioenergy would replace, and including economic analysis.

G29 Development of standardized methodologies and guidelines for determining the environmental sustainability of biomass harvesting.

CHAPTER 3

Research Activities, Infrastructure, and Institutional Arrangements

CHAPTER 3. RESEARCH ACTIVITIES, INFRASTRUCTURE, AND INSTITUTIONAL ARRANGEMENTS

The ability to answer the questions outlined in chapter 2 relies on research and monitoring activities and on the integration of the results of such activities into analysis and models. This chapter surveys research activities and infrastructure important for C science (see Figure 2). These are classified as contributing to (1) data acquisition and monitoring; (2) data storage and distribution; and (3) data analysis, integration, and synthesis. They are interconnected, feeding information to users, but also feeding information and questions to those who produce the knowledge. The chapter also discusses institutional arrangements that enable the alignment and integration of a broad range of multidisciplinary, multiorganizational efforts within a well-coordinated framework and an efficient transfer of relevant information to decision makers. Institutional arrangements are addressed under the following themes: (1) support, alignment, and coordination; (2) networking, training, and collaboration; and (3) knowledge transfer.

3.1 Research Activities and Infrastructure for Forest C Science

This section reviews the types of forest C science activities necessary to address the research goals described in chapter 2. For each activity, key uses and considerations for the next decade are outlined. Monitoring climate is a fundamental input for forest C science that is not addressed in this Blueprint.

3.1.1 Data acquisition: Monitoring, observations, and experiments

Forest inventories

Forest inventories provide basic information about forest attributes over time (e.g., forest cover, age, leading tree species, and biomass). Provincial/territorial agencies and the forest industry collect inventory information, and many have maintained networks of permanent inventory sample plots. The National Forest Inventory (NFI) started in 2000 under the auspices of the Canadian Council of Forest Ministers (CCFM) provides spatially explicit information from a sampling grid of ground plots collocated with photo plots covering Canada's entire land base. The generation of long time series of measurements contributes to the detection and

DATA ACQUISITION: MONITORING, OBSERVATIONS, AND EXPERIMENTS

Forest inventories	1.1, 1.2, 1.3, 3.1, 3.2, 4.1, 4.3
Remote sensing	1.1, 1.3, 3.1
Field studies	1.1, 1.2, 2.1, 2.2, 3.2, 4.3
Flux towers	1.1, 1.2, 1.3, 2.1, 3.2
Measurements of atmospheric C	1.3

DATA STORAGE AND DISTRIBUTION

Databases and information systems	1.1, 1.2, 1.3, 2.1, 4.2, 4.3

DATA ANALYSIS, INTEGRATION, AND SYNTHESIS

Bottom-up ecosystem modeling	1.1, 1.2, 1.3, 2.1, 2.2, 3.2, 4.1, 4.2
Top-down atmospheric modeling	1.3
Economic modeling	4.1, 4.2, 4.3

KNOWLEDGE TRANSFER

Knowledge transfer	All science questions

FIGURE 2. Research activities and infrastructure necessary for C science and for the relevant key forest C science questions discussed in chapter 2.

quantification of global change impacts. Such data are of great value for model parameterization, and remeasurements are essential for verification of model predictions. This information supports forest management and reporting on Canada's forests.

Two unique NFI contributions to C science are (1) estimates of total ecosystem C stocks derived from measurements using a consistent protocol, and (2) estimates of changes in ecosystem C stocks derived from consistent plot remeasurements. A national standardized plot network with ground-plot measurements in regular 5- or 10-year intervals enables the detection and reporting of forest C stock changes. The quantity and quality of this information are directly related to the frequency and number of measurements. Improved information on specific areas where current data are limited, such as soil and dead organic matter C pools, unmanaged forests, forested peatlands, permafrost distribution, and understory vegetation, can also help reduce uncertainties in forest C science. Some methodologies can maximize data collection, accessibility, and use. For example, statistical and modeling methods are being developed to increase the ability to spatially extrapolate sampling information, and increased use of remote sensing can improve sampling efficiency and help identify changes and long-term trends in

TABLE 2. Contribution of research activities and infrastructure to science questions.

	DATA ACQUISITION: MONITORING, OBSERVATIONS, AND EXPERIMENTS					DATA STORAGE AND DISTRIBUTION	DATA ANALYSIS, INTEGRATION, AND SYNTHESIS		
SCIENCE QUESTIONS	Forest inventories	Remote sensing	Field studies	Flux towers	Measurements of atmospheric CO_2	Databases and information systems	Bottom-up ecosystem modeling	Top-down atmospheric modeling	Economic modeling
1.1 What are the impacts of natural disturbances, forest management, and land-use change on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales?	+	+	+	+		+	+		
1.2 What are the impacts of climate variability, including drought, on current forest C dynamics from stand to national scales and from subannual to multidecadal time scales?	+	+	+	+		+	+		
1.3 How do local processes determining current forest C dynamics scale up to regional and national scales?	+	+		+	+	+	+	+	
2.1 To what extent will global changes alter C sources and sinks in Canada's forests?			+	+		+	+		
2.2 How will the impact of climate change on forest natural disturbances affect Canada's future forest C budget?			+				+		
3.1 How does the influence of forest C fluxes on climate compare to the influence of other processes and properties related to forest cover?	+	+							
3.2 What will be the contribution of Canada's forests to the future global GHG budget?	+		+	+			+		
4.1 What activities in forest ecosystems can best contribute to mitigation objectives?	+						+		+
4.2 What actions involving harvested wood products can best contribute to mitigation objectives?						+	+		+
4.3 What actions involving bioenergy from forest biomass can best contribute to mitigation objectives while ensuring the sustainability of biomass harvesting?	+		+			+			+

forest properties to focus monitoring efforts (see next section).

Canadian Space Agency

Remote sensing

Remote sensing is of particular interest given the remoteness and extent of Canada's forests. A growing range of sensors provide information such as forest cover properties, changes in forest attributes and cover over time, disturbance tracking, and timing and seasonality of phenological events and growing season length. For example, the Canada Centre for Remote Sensing (CCRS) develops image-processing protocols and offers Canada-wide coverage from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to map forest attributes. Through collaboration with the CFS, methods to produce annual change products at 250-m spatial resolution are being developed. Other examples include the use of various remote sensing products for deforestation monitoring and the Fire Monitoring, Accounting and Reporting System (FireMARS) (developed by the CCRS and the CFS) that provides data on annual area burned.

The power of remote sensing lies in its ability to cover large areas at various spatial resolutions and time intervals, and in the fact that current archives for certain sensors provide an ability to detect trends at regional to continental scales. The contribution of remote sensing to forest C science is expected to increase as technological capacity improves, and increasingly sophisticated C models call for more spatial data. Although the availability of remote sensing data increases and their cost decreases, data warehousing, assimilation, and processing require substantial capacities and resources. Improved integration between remote sensing and C science would optimize the use cost-effectiveness and relevance of data. For example, the North American Land Cover Monitoring System that uses MODIS data to provide monthly land cover information for all North America could inform C models. Integration requires ongoing dialogue to communicate the evolving potential of remote sensing products and the requirements of C science. Notwithstanding technical advances, remote sensing programs will continue to require ground-based measurements for calibration and validation.

Field studies

Field studies refer to a range of activities with a field work component. Types of field studies include chronosequence and transect studies, which use a series of sites to study how C dynamics evolve with time since disturbance or with changes in environmental conditions; retrospective analyses in which natural "archives" such as tree rings are used to study past climate or responses to changing conditions; and manipulative experiments in which ecosystem response to a treatment is quantified. Multiscale research and monitoring studies, such as Climate Impacts on Productivity and Health of Aspen (CIPHA), provide knowledge on annual changes of forest responses (including incidence and impact of pests, stand-level productivity, and mortality) in climatically sensitive areas, which improves the understanding of the climatic causes of forest change. This knowledge cannot be obtained from plot networks that are remeasured less frequently. Field studies generate basic information and knowledge needed for model development, validation, and linkages of remote sensing estimates.

Integrative modeling and synthesis can help identify knowledge gaps and inform the design of field studies and priority setting. For example, because the response of forest C fluxes to climate change will be strongly affected by the sensitivity of soil heterotrophic respiration (Rh) to changes in soil temperatures and moisture, targeted field studies (transects studies, soil-warming experiments) can be designed to better understand Rh response to climate change.

Flux towers

Flux towers are short-hand for a form of field studies in which highly specialized instruments mounted on towers above forest canopies provide continuous measurements of fluxes of CO_2, of water, and of energy between ecosystems and the atmosphere. Measurements over time capture forest responses to inter- and intra-annual climatic variability, and provide unique data for the development, parameterization, and verification of process models and for cross-scale data linkages. Towers located in chronosequences or across climatic gradients record the effects of time since disturbance and climate change on C dynamics. From 2002 to 2011, the Fluxnet-Canada Research Network/Canadian Carbon Program (FCRN/CCP) supported flux towers measurements; trained personnel; provided national standards for measurement, data processing, and data-archiving capacity; and acted as Canada's center of expertise for global initiatives in this field. No program has replaced FCRN/CCP. Canada's remaining flux towers measure the C dynamics of peatlands and the effects of harvesting, afforestation, and mountain pine beetle (*Dendroctonus ponderosae* Hopk.) outbreaks on C dynamics. Internationally, flux towers are located on over 500 sites across about 30 regional networks. In the US, a new National Ecological Observatory Network (NEON) will measure ecosystem processes, including CO_2 fluxes, over 20 years, and the European Union is establishing both a network of standardized, long-term GHG monitoring sites (Integrated Carbon Observation System or ICOS) and a research network to translate these data into policy-relevant analyses.

Establishment of flux tower stations in Canada was initially supported as research, but long-term operation is considered to be monitoring and rarely qualifies for research funding. Globally, a trend is observed toward the separation of the monitoring and research components of C science programs. Improved linkages between flux tower data and other ground measurements (permanent sample plots, tree rings, etc.) can further increase the utility and value of flux tower data, as will the development of process models parameterized and validated with flux tower data.

Measurements of atmospheric CO_2

High-accuracy and high-precision in situ and flask measurements of atmospheric CO_2 contribute to reducing the uncertainty in the determination of terrestrial sources and sinks of C, which can contribute to improved predictive models and a deeper understanding of the global carbon cycle. These CO_2 concentration measurements are used in atmospheric inversion models (see below) to generate maps of CO_2 sources and sinks at subcontinental scales or better. Environment Canada (EC) operates a network of 12 tower-based CO_2 measurement sites, a small number relative to the extent of Canada's forest land, limiting the spatial resolution of results. Some measurement sites were collocated with FCRN/CCP flux towers sites to facilitate the integration of the two types of measurements. Both the NEON and ICOS programs described previously integrate flux tower and atmospheric high-precision measurements.

The joint assimilation of observations from satellites and ground-based data is a promising method for quantifying CO_2 fluxes from forests with improved spatial and temporal resolution in the near future.

Although satellite observations of CO_2 do not match the high precision of ground-based in situ or flask CO_2 measurements, they greatly increase data coverage and contribute to improved CO_2 flux estimates. The Greenhouse Gases Observing Satellite (GOSAT) launched in 2009 is currently the satellite with observations most useful for improving inverse modeling estimates of CO_2 fluxes from forests, and the inverse modeling community has begun to work with GOSAT data. The quantity and quality of CO_2 observations from space are expected to increase rapidly after the launch of the NASA OCO-2 satellite in late 2014 or early 2015, China's TanSat around 2015, and other missions later in the decade, greatly increasing the CO_2 measurement coverage across Canada and the world.

3.1.2 Data storage and distribution

Databases and information systems

Scientific advances rely on our ability to share, synthesize, and integrate large quantities of data, and require database and information systems that allow multiple organizations and disciplines to contribute and access data within a common framework. The following provides a nonexhaustive list of existing databases. The National Forest Information System (NFIS) developed under the auspices of the Canadian Council of Forest Ministers compiles spatially referenced information from various national and provincial sources, although most data are only accessible to authorized users. The National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) is a system of databases, tools, and simulation models used to produce national-scale estimates of C stocks, emissions, and removals for Canada's managed forest that is used to meet C reporting needs and policy analysis. Other systems include the National Forestry Database (NFD); FireMARS; the Canadian Wildland Fire Information System (CWFIS); the System of Agents for Forest Observation Research with Automation Hierarchies (SAFORAH); and national databases on tree-ring analyses. Numerous provincial and territorial databases on forest pests and fire, meteorology, and air quality also exist. Archiving databases such as the FCRN/CCP-Data Information System (DIS) ensure that the results of past research remain available for C science.

Currently, none of the systems listed previously are designed for interoperability. Better integration of these databases will improve the capacity to answer policy questions, help identify data gaps, and prioritize data acquisition. The use of standardized protocols for data collection and management as well as strong coordination and interoperability among systems will facilitate integration. Ensuring availability and accessibility of databases to all relevant stakeholders and encouraging rapid dissemination of results increase scientific efficiencies, capacity, and synergy, and will contribute to better incorporation of C science knowledge into decision making. Consistent archiving of data generated from smaller-scale research can ensure this information is not lost to the science community. To understand and model large-scale responses, fine-scale information needs to be available and accessible to the research and modeling communities. Still needed is a coordinated compilation, documentation, and archiving coupled with improved, centralized access to large forest information databases such as the NFI, the various networks of permanent sample plots, the historical records from insect and disease surveys, the various sets of tree-ring data, the spatially referenced climate data and projections, and the various sets of flux tower data.

3.1.3 Data analysis, integration, and synthesis

Bottom-up ecosystem modeling

Empirical and process-based models are used to estimate forest C budgets and to project the impacts of human activities and climate change on forest C. This information is used to meet reporting requirements, and to assess forest sector mitigation potential. Such analyses require models of both forest C dynamics and models of the fate of harvested C in the forest sector. Most process-based models (e.g., BEPS, Can-IBIS, CN-CLASS, EALCO, *ecosys*, InTEC, 3PG) were developed in universities with contributions from researchers from government institutions. Regional empirical forest C budget models have also been developed, for example, the Ontario FORCARB-ON Model. C estimates for Canada's entire managed forest are generated by the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) that is part of NFCMARS. CBM-CFS3 is available free and is also used for project-level and regional-scale analyses in Canada and internationally. Both FORCARB-ON and CBM-CFS3 models rely on empirical yield data to describe forest growth rates and to simulate the impacts of natural disturbances, forest management, and land-use change.

Despite their capabilities and record of contribution to answering policy questions, modeling approaches still display shortcomings, as shown by two major retrospective model intercomparisons conducted as part of the FCRN/CCP Historical Carbon Modeling Project. There is limited agreement among process models about the magnitude, and in some cases direction, of responses of C dynamics to environmental variation. Modeling improvements depend largely on obtaining more detailed empirical data for use as a direct input for empirical models and for calibration of process-based models. Improved understanding on how tree growth and mortality will change under a changing climate is especially important. More generally, modeling efforts need to better integrate economic and biophysical analyses, account for C storage in harvested wood products, quantify substitution benefits, and incorporate non-GHG effects of land cover changes that affect climate, such as changes in albedo.

Top-down atmospheric modeling

Atmospheric inversion models use atmospheric CO_2 measurements to generate maps of CO_2 sources and sinks, typically at subcontinental scales, but often at finer spatial resolution. The US National Oceanic and Atmospheric Administration (NOAA) CarbonTracker assimilation system is an example of inversion model systems that use Canada's high-precision in situ and flask CO_2 measurements, along with additional observations across the globe. In Canada, the expertise in inverse modeling of CO_2 sources and sinks is limited but rapidly evolving. Environment Canada in collaboration with Canadian universities and supported by the Canadian Space Agency is developing a sophisticated assimilation system to estimate CO_2 sources and sinks, along with rigorous estimates of their uncertainties.

The system will use both high-precision ground-based data and satellite observations of CO_2, which will increase measurement coverage relative to the traditional approach and enable estimation of CO_2 fluxes at higher spatial and temporal resolution. This top-down atmospheric inverse modeling approach provides an estimate of forest C fluxes independent of other methods. Better linkages between top-down and bottom-up models will enable progress toward the integration and closure of GHG balances across continental scales.

Economic modeling

Economic analyses of how forest C management can contribute to climate change mitigation objectives are needed for examining policy trade-offs and providing sound policy advice. A range of economic models (e.g., optimization, bottom-up accounting, econometric) have been used to provide estimates of mitigation potential taking into account both biophysical (GHG) and economic influences. Cost estimates of mitigation are important because what may be a sound option technically (i.e., it will result in emission reductions or increased carbon sequestration) may not be best from an economic or policy perspective when the full suite of socioeconomic costs and benefits are considered, and when costs of forest C mitigation options are compared to options in other sectors.

Economic modeling of mitigation options involving forest C is less advanced than analysis of how human activity affects C, reflecting the fact that assessment of economics adds another level of complexity to mitigation assessment. To date, Canadian economic modeling of forest C mitigation has focused largely on the potential of afforestation. Much more modeling of the biophysical and economic aspects of how changes in forest management practices and harvested wood use could contribute to mitigation is especially needed, as is modeling that examines the relationship between mitigation and the multiple other goals of forest management. As well, it is critically important, for realistic estimates of long-term economic mitigation potential, that possible adaptation policies and the possible implications of climate change for forests are considered. Modeling involving a range of approaches and investigating a range of assumptions about the policy regime and other key influences, such as prices and discount rates used to convert future dollar values to current dollar values, will be useful.

3.2 Institutional Arrangements

Chapter 2 of this Blueprint emphasizes the importance and diversity of issues to be addressed by forest C science in Canada. The first section of chapter 3 shows how C science requires research in numerous disciplines, measurement and monitoring at multiple scales, and significant modeling efforts. Given this complexity, forest C science calls for the contribution from a broad range of players from a diversity of governmental and nongovernmental organizations. The following sections outline some principles that can support the efficient bridging between scientific activities and policy needs.

3.2.1 Support and coordination

Given the multidisciplinary, multiscale, and often long-term nature of forest C science, achievement of policy-level benefits requires long-term planning and funding as well as coordination. Canada's current capacity in forest C cycle science derives largely from the financial support and coordinating role of past initiatives such as the Enhancement of Greenhouse Gas Sinks component of the Program of Energy Research and Development (EGGS PERD) of the federal government, the Canada–United States Boreal Ecosystem-Atmosphere Study (BOREAS) project from the mid-90s, the Fluxnet-Canada Research Network (FCRN) and its successor the Canadian Carbon Program (CCP), and the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). Individual forest C science projects by universities are also supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), although increased requirement for industrial partnership now mostly precludes the development of large NSERC-funded projects or networks on forest C. The federal government supports forest C science through regular research funding to Natural Resources Canada (NRCan—the CFS and the CCRS), EC, Agriculture and Agri-Food Canada, and Parks Canada and through programs such as the Clean Air Agenda. Certain provincial agencies have also made substantial investments in forest C cycle science.

Notwithstanding past successes, new challenges and increasing demand for forest C information call for an ongoing, coherent, and well-coordinated approach to forest C science in Canada over the next decade. Several initiatives that have supported forest C science have ended, and funding from NSERC focuses on discovery research and shorter-term science. Some critical activities (e.g., monitoring) and areas of research (e.g., peatland) are now being supported by short-term funding, while others have been terminated.

This Blueprint is designed to inform organizations that support forest C science. It will ideally help agencies implement their multiyear, joint, or complementary C science programs, each supporting a variety of

coordinated C science activities. Its goal is to ensure that forest C science priorities are addressed, research results contribute to shared goals, and that Canada plays a leading role in the global forest C science community.

3.2.2 Training, networking, and collaboration (domestic and international)

Ongoing training of forest C scientists and technicians is necessary to maintain and strengthen the scientific capacity for the anticipated challenges of the 21st century. Because of the diversity of expertise and institutions involved in forest C science, effective networking and collaboration among the different players can help minimize duplication of efforts and maximize synergies. Collaboration between federal and provincial governments, universities, and other research centers accelerates the discovery process through comparison and validation of results and methods. Collaboration with international efforts helps maintain a global perspective, ensures Canadian efforts remain at an international caliber, and provides a venue through which the contributions of Canada's forests may be properly represented in international fora.

The FCRN/CCP has been a training hub of highly qualified personnel, and its members have contributed to several international synthesis papers, providing unique insights on the global terrestrial C cycle. Annual general meetings on terrestrial C science that were held from 2003 to 2010 by the FCRN/CCP have contributed greatly to the establishment of a strong and networked forest C science community in Canada. They also documented the evolution of scientific knowledge and policy questions, seeding new ideas and collaborations, enabling cross-fertilization between disciplines, and maintaining focus and integration among activities. Before the FCRN/CCP meetings, PERD annual meetings on C science hosted by EC played the same role for federal scientists.

Collaboration occurs largely on an ad hoc basis domestically and internationally. An example of cooperation between organizations with complementary mandates is the collaboration between the CFS and the CCRS in the development of remote sensing tools for disturbance monitoring (fire and insects). The CFS also collaborates with EC, which is the main provider of climate science, and delivers climate data, GHG measurements, modeling, and research. CarboNA is a joint government-level initiative between Canada, the US, and Mexico whose goal is to establish greater cohesion across North America in C science through the identification of continental-scale priority issues and promotion of collaborative research in areas of common interest and complementary expertise. Scientists researching forest C cycles in Canada have also contributed to the Intergovernmental Panel on Climate Change (IPCC) assessment reports, special reports, and greenhouse gas reporting guidelines.

The continuous development of expertise, networking, and cooperative work within the forest C science community is integral to the success of C science. Initiatives that would support the development and nurturing of C science human capacity and network include holding annual meetings, providing secondment and training opportunities domestically and abroad, and encouraging individual scientists as well as institutions to participate in and contribute to international scientific programs.

3.2.3 Knowledge transfer

Science can contribute to policy goals only if the knowledge acquired is accessible to and applicable by decision makers. Efficient knowledge transfer mechanisms help align the generation and tailoring of information to meet the different demands of forest policy makers, ranging from international negotiation to land-use and forest management planning. Several decision-support systems have been developed and applied to decision making related to forest C in the last few decades (e.g., NFCMARS, CBM-CFS3, FORCARB-ON). The CFS supports and trains researchers, government analysts, and industry personnel in the use of CBM-CFS3. Peer-reviewed journal articles, technical transfer notes, and policy notes are also efficient means by which knowledge is exchanged between the C science and policy communities. Science-based presentations to domestic and international audiences, and videos of such presentations are also effective in transferring knowledge to a broader community.

Science is often developed unidirectionally. An ongoing dialogue between the science and policy communities during knowledge generation and transfer helps ensure the final uptake of the scientific knowledge into the decision-making process. Ongoing and flexible data synthesis, modeling, and analysis activities for forest ecosystems and the forest product sector are required to meet the growing policy demand. Efficient knowledge transfer such as the development and support of decision-support tools, maps and databases, workshops and training, media, and ever-advancing technology, including Web-based information portals, could play an important role in meeting this challenge.

CHAPTER 4

Implementing the Blueprint

©iStockphoto.com/Steve Cole

CHAPTER 4. IMPLEMENTING THE BLUEPRINT

Scientific research (chapter 2) supported by technology and infrastructure (chapter 3) enables the description of the current state of forest C, the tracking of its changes over time, the projection of its possible future states, and assessment of the human and environmental influences that drive C dynamics. Over the past decade, advances in Canadian forest C science in these areas have provided crucial information to support federal, provincial, and territorial policy decisions and forest management. These successes reflected long-term investments in research, enabling the development of interdisciplinary projects of government and university scientists to advance understanding, integrate data, and synthesize results. This concluding chapter proposes actions that, if initiated soon and sustained to 2020, will ensure that Canada's forest C science continues this success and meets future policy requirements. Ongoing investment in forest C science activities, expertise, and infrastructure will be needed, but estimating investment levels and corresponding results is beyond the scope of this document. The speed and breadth of development of new knowledge and information, and their contribution to policy, will vary depending on the level of investment.

This Blueprint does not provide a unique path forward but rather identifies key science questions and research goals that can orient activities of research organizations and guide research-funding decisions. Needs of different stakeholders vary depending on their particular circumstances, and so will the importance they attach to the various science and policy themes and questions discussed in this document. We hope that the Blueprint will be used as a guide for research and for the critically important tasks of coordination and integration of Canadian forest C science. A coordinated and integrated approach—with a vision of what could be achieved by 2020—will strengthen the impact of research and its contribution to policy questions, for example, by ensuring complementarity of research activities, integration of databases, and creation of compatible analytical tools. Building on the actions proposed here, an initial vision for an integrating system for forest C science in Canada is offered in the box that follows. The forest C science and policy communities will need to discuss and refine this initial vision before implementation.

Actions to Implement the Blueprint

Strengthen networking and knowledge exchange in the forest C science and policy communities. This should increase the quality of science, the efficiency of the scientific endeavor, the relevance and effective application of science to policy, and the uptake of its results by the policy community. Conferences, workshops, and training programs, as well as collaborative Web-based sites and knowledge-sharing tools, can contribute to disseminating research results, exploring what they mean for policy, and building common understanding of emerging policy questions.

Improve frameworks for forest C data integration, synthesis, and analysis. Different tools may be needed to address issues relevant to federal or provincial governments, industry, or other interested parties. Frameworks could build on existing tools and incorporate up-to-date spatially explicit databases of forest information. Data should be shared among frameworks so that analyses will be coherent across scales.

Quantify with reduced uncertainty the impacts of environmental drivers on forest C dynamics. Significant uncertainty still exists around key C pools (dead organic matter and soil organic matter) and ecosystem processes (stand growth, mortality, succession, and permafrost thawing) and how they are impacted by environmental conditions and changes in those conditions. Models that enable assessment and projection from stand to national scales are parameterized and validated with empirical observations and time series from field studies and remote sensing. Model improvement requires these observational data and knowledge gained from experimental and observational research on the effects of environmental changes on ecosystem C dynamics.

Quantify with reduced uncertainty the impacts of human activities on forest C dynamics, including forest management, harvesting, protection, and conservation strategies. Although some information

Vision for an Integrating System for Forest C Science in Canada

In 2020, Canada will continue to be a leader in forest C science with a strong capacity to address forest C policy issues and analytical needs at multiple levels. Nationally, Canada will use a second-generation forest C monitoring and reporting system that will (1) be spatially explicit with a high spatial resolution; (2) include both managed and unmanaged forests; (3) be updated annually with information on natural disturbances, climate, and human activities; (4) better represent global change impacts on C dynamics; and (5) include harvested wood products and their role in storing C and in reducing emissions when substituted for more energy-intensive materials.

The system will be centrally designed and maintained but highly modular to allow for a variety of modeling approaches and flexibility in application. It will integrate models that account for CO_2 and other GHG fluxes but will also allow for inclusion of results from complementary analyses such as changes in albedo and hydrological cycles.

The system will be open source to maximize transparency, cooperation across research teams, and application of science to meet policy needs. Information from many sources, results of analyses, and decision-support products will be accessible to federal, provincial, and territorial government agencies; universities; industry; and the public through Web-based systems.

The system will be linked closely with forest inventory and remote sensing systems that provide periodic spatially explicit data on forest ecosystems. Information from a national network of photo and ground plots (from the NFI and other sources) will allow model calibration. Remeasurements of ground plots following a consistent protocol will provide nationally distributed estimates of site-level C dynamics to verify medium (five-year) and longer-term (multidecadal) projections of change in forest ecosystem C stocks.

The system will access spatially interpolated climate variables across Canada's forests for past climate as well as for projected climate scenarios. This will allow the estimation of climate-related changes in forest growth, mortality, and C dynamics and help project future forest characteristics. Comparisons between projected and observed forest changes will allow model improvement and knowledge gap identification.

The system will be designed and implemented to allow uncertainty assessments and statistical estimates of error propagation.

The system development will involve dialogue and collaboration with international efforts to ensure cohesion, particularly with systems in the United States and Mexico. Monitoring will be coordinated with international initiatives (e.g., ICOS in Europe, NEON in the United States, TERN (Terrestrial Ecosystem Research Network) in Australia) to ensure that Canada meets international standards and that international efforts benefit from Canadian science.

The system will provide decision and policy support, and facilitate the integration of biophysical and economic information. It will be used for both assessments (looking backward) and projections (looking into the future), and contribute information to develop climate mitigation and adaptation strategies.

exists on forest management impacts on C dynamics, significant uncertainties remain regarding silvicultural practices (e.g., partial retention cutting, site preparation) and the interactions between environmental changes and management actions. Improving the quantification of human impacts on forest C dynamics will provide knowledge required for the design of climate change mitigation portfolios.

Expand forest C budget analyses to Canada's entire forest area. Carbon dynamics are poorly quantified for forested peatland and permafrost systems, and for the unmanaged forest. Although not included in current international GHG reporting obligations, the C pools of these vast regions are projected to contribute large future C emissions due to their size and vulnerability to warming temperatures. Better quantification and understanding of these pools and fluxes are required to reduce the large uncertainties in the assessment of feedbacks between terrestrial C dynamics and climate change.

Improve spatial coverage, accuracy, and timeliness of forest inventory information. A national network of ground plots where total ecosystem C stocks are remeasured periodically (every 5–10 years) using consistent methodology is the basic requirement. Currently, the NFI is the only systematic remeasurement program of total forest C stocks in Canada and is the only national-scale data source with repeated measurements of dead organic matter and soil C pools.

Generate in a timely manner the annual statistics on areas affected by fires, insects and diseases, forest management, and land-use changes. Such statistics are already produced but efficiencies and improved timeliness likely could be achieved through integrated use of new remote sensing products and interagency sharing of relevant information.

Enable spatial and temporal extrapolation of C fluxes. Coordinated monitoring of C fluxes based on an optimally designed network of flux towers and integration of flux towers measurements with inventory and remote sensing data is the basis for this activity. Flux towers are currently the only technology that provides real-time measurements of stand-level C flux responses to environmental drivers.

Integrate forest C science into larger-scale assessments of C fluxes. Forest C models provide inputs to atmospheric inversion models that estimate fluxes from land surfaces. Combining such tools with satellite measurements of atmospheric CO_2 concentrations provides a way to verify regional and continental C balances.

Generate interdisciplinary assessments of the biophysical and economic implications of forest C mitigation options. Incorporating this knowledge in the development of decision-support tools will help forest managers and policy makers determine potential options and identify trade-offs among these options and the implications for other forest management goals.

Train and develop the next generation of C science experts. Ensuring awareness of policy issues and fostering science–policy integration are crucial. This requires close cooperation between government institutions and universities, and ongoing dialogue and collaboration with the international community.

GLOSSARY

Note: Unless otherwise indicated, the source of all definitions is IPCC (2007a & b).

adaptation: Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects.

afforestation: Direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding, and/or the human-induced promotion of natural seed sources.

albedo: The fraction of solar radiation reflected by a surface or object, often expressed as a percentage.

anthropogenic emissions: Emissions of greenhouse gases, greenhouse gas precursors, and aerosols associated with human activities, including the burning of fossil fuels, deforestation, land-use changes, livestock, fertilization, cement manufacturers, etc.

biomass: Total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass.

Boreal Ecosystem-Atmosphere Study (BOREAS): Large-scale experiment initiated in 1990 to investigate the energy, water, and C interactions between the boreal forest biome and the atmosphere. http://daac.ornl.gov/BOREAS/boreas.shtml [Accessed May 2012.]

Boreal Ecosystems Productivity Simulator (BEPS): Remote sensing approach to quantifying the terrestrial C cycle. BEPS uses satellite data to map the net primary productivity (NPP) (see below). BEPS has recently been expanded through the Integrated Terrestrial Ecosystem Carbon Model (InTEC) (see below). http://faculty.geog.utoronto.ca/Chen/Chen's%20homepage/res_beps.htm [Accessed May 2012.]

Canada Centre for Remote Sensing (CCRS): Government of Canada's (Department of Natural Resources) center of excellence for remote sensing and geodesy. In partnership with many government stakeholders, through strong links to academia and the private sector, and via international collaborations, the CCRS ensures that accessibility of satellite data serves the public needs. http://ccrs.nrcan.gc.ca/index_e.php [Accessed May 2012.]

Canada-specific version of the Integrated Biosphere Simulator (Can-IBIS): Model that integrates stand-level physiology and competition among plant functional types together with landscape-scale atmospheric exchange processes to create climate-sensitive simulations of large-scale (continental to global) vegetation development and climate feedbacks (D. Price, pers. comm., 2011).

Canadian Carbon Program (CCP): Program following the Fluxnet Canada Research Network (2007–2011) which, in addition to the Canada-wide measurement infrastructure, carried out increased activities in integration and modeling, global syntheses, and collaboration with the CFS carbon accounting project. Funding to CCP ceased in the summer of 2011 (P. Bernier, pers. comm., 2012).

Canadian Fire Effects Model (CanFIRE): A compilation of Canadian fire behavior models that are used to calculate first-order (immediate, physical) fire effects on stand characteristics, and to simulate the resulting second-order (later, ecological) fire effects on stand composition. http://www.glfc.forestry.ca/canfire-feucan/ [Accessed May 2012.]

Canadian Foundation for Climate and Atmospheric Sciences (CFCAS): Autonomous nonprofit agency that provided support for university-based research on weather and climate. Formally established in 2000–2001, the CFCAS was terminated in March 2012. http://www.cfcas.org/ [Accessed May 2012.]

Canadian Wildland Fire Information System (CWFIS): Computer-based fire management information system that monitors fire danger conditions across Canada. Daily weather conditions are collected from across Canada and used to produce fire weather and fire behavior maps. In addition, satellites are used to detect fires. The CWFIS is responsible for creating daily fire weather and fire behavior maps and hot spot maps. http://cwfis.cfs.nrcan.gc.ca/en_CA/index [Accessed May 2012.]

C- and N-coupled Canadian Land Surface Scheme (CN-CLASS): Model of surface–atmosphere exchanges of CO_2, water vapor, and energy. The model incorporates a process-based two-leaf (sunlit and shaded) canopy conductance and photosynthesis submodel in the Canadian Land Surface Scheme (CLASS). The model can simulate half-hourly, daily, and monthly mean CO_2 exchange and evaporation values in both deciduous and coniferous forests (Arain et al. 2006).

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3): Stand and landscape-level modeling framework to simulate the dynamics of all forest C stocks required under the United Nations Framework Convention on Climate Change (aboveground biomass, belowground biomass, litter, dead wood, and soil organic C). It is compliant with the C estimation methods outlined in the report IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003). http://carbon.cfs.nrcan.gc.ca/CBM-CFS3_e.html [Accessed May 2012.]

carbon cycle: The flow of C (in various forms, e.g., as CO_2) through the atmosphere, ocean, terrestrial biosphere and lithosphere.

carbon models: A tool for the calculation and reporting of ecosystem C stocks and fluxes. C models can use a variety of approaches with different types of input data, and can operate on a wide range of spatial and temporal scales. Some examples of different types of C models include empirical, inversion, and process-based models (W. Kurz, pers. comm., 2012).

CarbonTracker: Data assimilation system used to provide a consistent estimate of surface CO_2 exchange. Built by the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL), which monitors CO_2 in the atmosphere as a contribution to the North American Carbon Program (NACP) (Peters et al. 2007).

Clean Air Agenda: Government of Canada's 10-year comprehensive plan responding directly to key government priorities and Canadian concerns about air quality. The government renewed funding for the Clean Air Agenda in Budget 2011.

climate: The average weather, or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind.

climate change: A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

deforestation: The nontemporary conversion of forest land to nonforest.

Ecological Assimilation of Land and Climate Observations (EALCO): Physically based numerical model developed to simulate the ecological processes of terrestrial ecosystems using Earth observations. EALCO has been used mainly in studying land surface albedo and the fraction of absorbed photosynthetically active radiation, ecosystem water cycle and surface water–groundwater interactions, and plant and soil C and N dynamics using satellite observations (S. Wang, pers. comm., 2012).

***ecosys*:** Three-dimensional process-based ecosystem mathematical model that represents a range of site-specific conditions and therefore accounts for the effect of site-specific past and current land use, climate, soil type, topography, etc., on GHG emissions (Metivier et al. 2009).

feedback: An interaction mechanism between processes in the climate system is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Fire Monitoring, Accounting and Reporting System (FireMARS): National wildland fire C emissions reporting system developed by NRCan. The system is the overall structure that integrates satellite-detected hot spots to record daily fire growth, and final burned area; ground-based daily fire weather as monitored by the CWFIS; stand-level C emissions and pool transfers during fire as calculated by CanFIRE; and pre-fire fuel loading and final C pool change summary by CBM-CFS3 (B. de Groot, pers. comm., 2011).

Fluxnet-Canada Research Network (FCRN): Former (2002–2007) national research collaborative network (government, universities, and industry) that studied the influence of climate and disturbance on C cycling in Canadian forest and peatland ecosystems. The network had 22 research sites distributed among 7 stations conducting continuous measurements of CO_2, water, and energy exchanges between ecosystems and the atmosphere using the eddy covariance flux measurement technique. The infrastructure and data of this research network were transitioned to the Canadian Carbon Program (CCP) in early 2007 (P. Bernier, pers. comm., 2012).

Fluxnet-Canada Research Network/Canadian Carbon Program Data Information System (FCRN/CCP-DIS): An Internet-accessible database in which are stored flux, climate, site characteristic, and ecological data, and dataset documentation from Canadian flux towers sites that were affiliated with the Canadian Carbon Program and its predecessor Fluxnet-Canada. The CCP-DIS data are available free to investigators in standardized, flat-ASCII format. The CCP-DIS will be operated and housed by Environment Canada at the National Hydrology Research Centre in Saskatoon until at least March 31, 2012. (P. Bernier, pers. comm., 2012). ftp://daac.ornl.gov/data/fluxnet/fluxnet_canada/ [Accessed May 2012.]

Forest Carbon Budget Model for Ontario (FORCARB-ON): C budget model for Ontario used to determine the current and future forest C balance in Ontario's managed forest using provincial forest resources inventory data and information about planned forest management activities. (http://www.mnr.gov.on.ca/en/Business/OFRI/2ColumnSubPage/STEL02_165418.html). [Accessed May 2012.]

greenhouse gas (GHG): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), halocarbons, and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere.

harvested wood products (HWP): Wood-based materials harvested from forests that are used for products such as furniture, plywood, paper and paper-like products, or for energy. http://www.unece.org.unecedev.colo.iway.ch/forests/outlook/carbonstorage.html [Accessed May 2012.]

heterotrophic respiration (Rh): The conversion of organic matter to carbon dioxide by organisms other than plants.

Integrated Carbon Observation System (ICOS): A research infrastructure to decipher the greenhouse gas balance of Europe and adjacent regions. The main objectives of ICOS are (1) to provide the long-term observations required to understand the present state and predict future behavior of the global C cycle and greenhouse gas emissions; and (2) to monitor and assess the effectiveness of C sequestration and/or greenhouse gases emission reduction activities on global atmospheric composition levels, including attribution of sources and sinks by region and sector. http://www.icos-infrastructure.eu/index.php?p=hom [Accessed May 2012.]

Integrated Terrestrial Ecosystem Carbon Model (InTEC): Model that integrates the impacts of (1) disturbances, (2) management practices, (3) climatic factors, and (4) atmospheric factors, and estimates their effects on the annual C cycle of a forest region. InTEC is based on the Farquhar's leaf photosynthesis model, the Century C cycle model for soil C modeling, the net N mineralization model, and an age–net primary productivity relationship derived from forestry inventory-based age–biomass relationships. http://faculty.geog.utoronto.ca/Chen/Chen's%20homepage/res_intec.htm [Accessed May 2012.]

land use and land-use change (LULUC): Land use refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land-use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the surface albedo, evapotranspiration, sources, and sinks of greenhouse gases, or other properties of the climate system and may thus have a radiative forcing and/or other impacts on climate, locally or globally.

mitigation: Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.

Moderate Resolution Imaging Spectroradiometer (MODIS): A key instrument aboard the Terra and Aqua satellites which orbit the earth. Terra MODIS and Aqua MODIS are viewing the entire earth's surface every 1–2 days, acquiring data in 36 spectral bands, or groups of wavelengths. These data help in understanding global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere. http://modis.gsfc.nasa.gov/about/ [Accessed May 2012.]

National Ecological Observatory Network (NEON): A project of the US National Science Foundation, with various other US agencies and NGOs cooperating, that collects data across the US on the impacts of climate change, land-use change, and invasive species on natural resources and biodiversity. The network is designed to detect and enable forecasting of ecological change at continental scales over multiple decades. http://www.neoninc.org [Accessed May 2012.]

National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS): Canada's forest C reporting system aims to estimate forest C stocks, changes in C stocks, and emissions of non-CO_2 greenhouse gases in Canada's managed forests. NFCMARS is designed to estimate past changes in forest C stocks—that is, from 1990 to 2006 (monitoring)—and to predict, based on scenarios of future disturbance rates and management actions, changes in C stocks in the next two to three decades (projection). http://carbon.cfs.nrcan.gc.ca/ForestCarbonAccount_e.html [Accessed May 2012.]

National Forest Information System (NFIS): An initiative providing Web tools ranging from simple portrayal to sophisticated analyses to users worldwide. Users can discover, integrate, and display this current, authoritative, and accurate information on Canada's forests and on sustainable forest management. https://ca.nfis.org/about_eng.html [Accessed May 2012.]

National Forest Inventory (NFI): A collaborative (provincial and territorial jurisdictions and the federal government) program that continuously monitors a network of sampling points covering 1% of Canada's land mass to provide accurate, timely, and consistent information on the state and sustainable development of Canada's forests. https://nfi.nfis.org/home.php?lang=en [Accessed May 2012.]

National Forestry Database (NFD): A collaborative partnership between the federal and provincial governments that aims (1) to describe forest management and its impact on the forest resource; (2) to develop a public information program based on the database; and (3) to provide reliable, timely information to the provincial and federal policy processes. The program compiles national statistics regarding Canadian forests and forest resources. http://nfdp.ccfm.org/about_us_e.php [Accessed May 2012.]

National Oceanic and Atmospheric Administration (NOAA): A US agency that uses a comprehensive understanding of the role of the oceans, coasts, and atmosphere in the global ecosystem to keep the public informed of the changing environment around them, and to help make social and economic decisions. Among other products and services, the NOAA provides daily weather forecasts, severe storm warnings, and climate monitoring to fisheries management, coastal restoration, and supporting marine commerce. http://www.noaa.gov/about-noaa.html [Accessed May 2012.]

Natural Sciences and Engineering Research Council of Canada (NSERC): A Canadian agency that supports university students in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian companies to participate and invest in postsecondary research projects. http://www.nserc-crsng.gc.ca/index_eng.asp [Accessed May 2012.]

net biome productivity (NBP) and net ecosystem C balance (NECB): Net ecosystem productivity (NEP) minus exports of C due to fire, harvest, and transport of dissolved organic C in streams is referred to as NECB. When summed over a larger time scale and over many land units to provide a regional value, it is referred to as NBP (T.A. Black, pers. comm., 2011).

net ecosystem exchange (NEE) and net ecosystem productivity (NEP): Net uptake of CO_2 by an ecosystem obtained as NEP=−NEE. Positive values indicate that the ecosystem is taking up C from the atmosphere while negative values indicate that the ecosystem is losing C to the atmosphere. It is the difference between gross ecosystem photosynthesis (GEP) (or gross primary productivity, GPP) and ecosystem respiration (Re), that is, NEP=GEP−Re. It is also equal to net primary productivity minus heterotrophic respiration (T.A. Black, pers. comm., 2011).

net primary productivity (NPP): NPP is a parameter used to quantify the net carbon absorption rate by living plants. NPP is the difference between plant photosynthesis and respiration which releases part of the carbon absorbed, that is, NPP = Photosynthesis Rate−Plant Respiration Rate (expressed in units of gram carbon/square metre/year). http://faculty.geog.utoronto.ca/Chen/Chen's%20homepage/res_npp.htm [Accessed May 2012.]

permafrost: Ground (soil or rock including ice and organic material) that remains at or below 0°C for at least two consecutive years (van Everdingen 1998).

Program of Energy Research and Development (PERD): A federal program operated by Natural Resources Canada that funds research and development to ensure a sustainable energy future for Canada. PERD's subprogram for the Enhancement of Greenhouse Gas Sinks (PERD EGGS) focused on increasing our understanding of GHG cycles, improving our capacity to report human-induced GHG fluxes in Canadian ecosystems, and advising policy makers on potential mitigation actions. PERD EGGS concluded in 2007.

sink: Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere.

System of Agents for Forest Observation Research with Automation Hierarchies (SAFORAH): A system developed through a collaboration of government, university, and industry that coordinates and streamlines the archiving and sharing of numerous distributed large remote sensing data sets between various research groups with the CFS, the University of Victoria, and other academic and government partners to facilitate research in support of our national forest monitoring activities. http://www.saforah.org/ [Accessed May 2012.]

Terrestrial Ecosystem Research Network (TERN): An overarching and integrated network designed to serve ecosystem research in Australia that builds on significant past investments by scientists and governments to understand Australian ecosystems by focusing on collating, calibrating, validating, and standardizing existing data sets. TERN is also funding new research infrastructure and collection systems, expanding observation and monitoring programs into unrepresented ecosystems, and building digital infrastructure to store and publish this information in a form that can be searched and accessed free under licenses that acknowledge the data provider(s) and build collaborative research. http://www.tern.org.au/ [Accessed May 2012.]

3PG: Generalized forest C allocation model used to derive monthly estimates of gross primary productivity, C allocation, and stand growth. http://www.fsl.orst.edu/mycology/ss/3PG.htm [Accessed May 2012.]

REFERENCES

Arain, M.A.; Yaun F.; Black T.A. 2006. Soil–plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada. Agric. For. Meteorol. 140(1–4):171–192. http://dx.doi.org/10.1016/j.agrformet.2006.03.021 [Accessed May 2012.]

[CCFM] Canadian Council of Forest Ministers. 2008. A vision for Canada's forests: 2008 and beyond. Canadian Council of Forest Ministers. Ottawa, ON. 15 p. http://www.ccfm.org/pdf/Vision_EN.pdf [Accessed May 2012.]

[CCFM] Canadian Council of Forest Ministers. 2009. A framework for forest management offset protocols. Climate Change Task Force, Canadian Council of Forest Ministers. Ottawa, ON. 142 p. http://www.ccfm.org/pdf/FFMOP_e.pdf. [Accessed May 2012.]

Environment Canada. 2012. National inventory report 1990–2010: Greenhouse gas sources and sinks in Canada. Executive summary. Canadian Government submission to the UN Framework Convention on Climate Change. Pollutant Inventories and Reporting Division, Environment Canada. http://www.ec.gc.ca/Publications/A91164E0-7CEB-4D61-841C-BEA8BAA223F9/Executive-Summary-2012_WEB-v3.pdf [Accessed May 2012.]

[IPCC] Intergovernmental Panel on Climate Change. 2003. IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry. J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner, eds. Prepared by the IPCC National Greenhouse Gas Inventories Programme. IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html [Accessed May 2012.]

[IPCC] Intergovernmental Panel on Climate Change. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, eds. Prepared by the IPCC National Greenhouse Gas Inventories Programme. IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html [Accessed May 2012.]

[IPCC] Intergovernmental Panel on Climate Change. 2007a. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds. Cambridge University Press, Cambridge, UK, and New York, NY. 996 p. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm [Accessed May 2012.]

[IPCC] Intergovernmental Panel on Climate Change. 2007b. Climate change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, eds. Cambridge University Press, Cambridge, UK, and New York, NY. 851 p. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm [Accessed May 2012.]

Metivier, K.A.; Pattey, E.; Grant, R.F. 2009. Using the *ecosys* mathematical model to simulate temporal variability of nitrous oxide emissions from a fertilized agricultural soil. Soil Biol. Biochem. 41(12):2370–2386; doi:10.1016/j.soilbio.2009.03.007. http://www.sciencedirect.com/science/article/pii/S0038071709000959 [Accessed May 2012.]

Metsaranta, J.M.; Dymond, C.C.; Kurz, W.A.; Spittlehouse, D.L. 2011. Uncertainty of 21st century growing stocks and GHG balance of forests in British Columbia, Canada resulting from potential climate change impacts on ecosystem processes. For. Ecol. Manag. 262(5):827–837.http://ac.els-cdn.com/S0378112711002799/1-s2.0-S0378112711002799-main.pdf?_tid=a3e7d2afa791825f40f092ed35a33bea&acdnat=1336073370_a4cd5d01b2286547c0ede4cb075f0704 [Accessed May 2012.]

Metsaranta, J.M.; Kurz, W.A.; Neilson, E.T.; Stinson, G. 2010. Implications of future disturbance regimes on the carbon balance of Canada's managed forest (2010–2100). Tellus 62(5):719–728. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0889.2010.00487.x/full [Accessed May 2012.]

Natural Resources Canada. 2011a. The State of Canada's Forests. Annual Report 2011. Canadian Forest Service, Ottawa, ON. 47 p.http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/32683.pdf [Accessed May 2012.]

Natural Resources Canada. 2011b. Canadian Forest Service: Terms. http://cfs.nrcan.gc.ca/terms [Accessed May 2012.]

Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; Ciais, P.; Jackson, R.B.; Pacala, S.W.; McGuire, A.D.; Piao, S.; Rautiainen, A.; Sitch, S.; Hayes, D. 2011. A large and persistent carbon sink in the world's forests. Science 333:988–993; doi:10.1126/science.1201609. http://www.sciencemag.org/content/333/6045/988.full.html [Accessed May 2012.]

Peters, W.; Jacobson, A.R.; Sweeney, C.; Andrews, A.E.; Conway, T.J.; Masarie, K.; Miller, J.B.; Bruhwiler, L.M.P.; Pétron, G.; Hirsch, A.I.; Worthy, D.E.J.; van der Werf, G.R.; Randerson, J.T.; Wennberg, P.O.; Krol, M.C.; Tans, P.P. 2007. An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker. PNAS 104(48):18925–18930.http://salix.atmos.colostate.edu/carbon/Carbon_Cycle/Inverse_Modeling_files/2007.CarbonTracker.PetersW_PNAS.pdf [Accessed May 2012.]

Stinson, G.; Kurz, W.A.; Smyth, C.E.; Neilson, E.T.; Dymond, C.C.; Metsaranta, J.M.; Boisvenue, C.; Rampley, G.J.; Li, Q.; White, T.M.; Blain, D. 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Global Change Biol. 17(6):2227–2244. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2010.02369.x/pdf [Accessed May 2012.]

van Everdingen, R.O., ed. 1998. (Revised May 2005.) Multi-language glossary of permafrost and related ground-ice terms. National Snow and Ice Data Center/World Data Center for Glaciology. Boulder, CO. http://nsidc.org/fgdc/glossary/. [Accessed May 2012.]

ABBREVIATIONS AND ACRONYMS

BEPS: boreal ecosystems productivity simulator

BOREAS: Boreal Ecosystem-Atmosphere Study

CanFIRE: Canadian Fire Effects model

Can-IBIS: Canada-specific version of the integrated biosphere simulator

CarboNA: North American Carbon Program (CarboNA) Science Plan

CBM-CFS3: Carbon Budget Model of the Canadian Forest Sector

CCFM: Canadian Council of Forest Ministers

CCP: Canadian Carbon Program

CCRS: Canada Centre for Remote Sensing

CFCAS: Canadian Foundation for Climate and Atmospheric Sciences

CFS: Canadian Forest Service

CIPHA: Climate Impacts on Productivity and Health of Aspen

CN-CLASS: C- and N-coupled Canadian Land Surface Scheme

CWFIS: Canadian Wildland Fire Information System

EALCO: Ecological Assimilation of Land and Climate Observations

EC: Environment Canada

***ecosys*:** three-dimensional process-based ecosystem mathematical model

EGGS: Enhancement of Greenhouse Gas Sinks program

FCRN: Fluxnet-Canada Research Network

FCRN/CCP-DIS: Fluxnet-Canada Research Network/Canadian Carbon Program Data Information System

FireMARS: Fire Monitoring, Accounting and Reporting System

FORCARB-ON: Forest Carbon Budget Model for Ontario

GHG: greenhouse gas

GOSAT: Greenhouse Gases Observing Satellite

HWP: harvested wood products

ICOS: Integrated Carbon Observation System

InTEC: Integrated Terrestrial Ecosystem Carbon model

IPCC: Intergovernmental Panel on Climate Change

LULUC: land use and land-use change

MODIS: Moderate Resolution Imaging Spectroradiometer

NACP: North American Carbon Program

NBP: net biome productivity

NECB: net ecosystem C balance

NEE: net ecosystem exchange

NEON: National Ecological Observatory Network

NEP: net ecosystem productivity

NFCMARS: National Forest Carbon Monitoring, Accounting and Reporting System

NFD: National Forestry Database

NFI: National Forest Inventory

NFIS: National Forest Information System

NOAA: National Oceanic and Atmospheric Administration

NPP: net primary productivity

NRCan: Natural Resources Canada

NSERC: Natural Sciences and Engineering Research Council of Canada

PERD: Program of Energy Research and Development

Rh: heterotrophic respiration

SAFORAH: System of Agents for Forest Observation Research with Automation Hierarchies

TERN: Terrestrial Ecosystem Research Network

3PG: physiological principles predicting growth

UNFCCC: United Nations Framework Convention on Climate Change

CONTRIBUTORS

Brian Amiro, University of Manitoba
Altaf Arain, McMaster University
Vivek Arora, Environment Canada
Ed Banfield, CFS, Ottawa, ON
Paul Barlett, Environment Canada
Alan Barr, Environment Canada
Michael Bartlett, Government of New Brunswick
Céline Beauparlant, formerly CFS; currently Citizenship and Immigration Canada
Robert Beauregard, Laval University
Pierre Bernier, CFS, Laurentian Forestry Centre, Québec, QC
Jag Bhatti, CFS, Northern Forestry Centre, Edmonton, AB
T. Andrew Black, The University of British Columbia
Céline Boisvenue, CFS, Pacific Forestry Centre, Victoria, BC
Darcie Booth, CFS, Ottawa, ON
Mark Boyland, CFS, Ottawa, ON
Michael Brady, CFS, Northern Forestry Centre, Edmonton, AB
Al Cameron, CFS, Great Lakes Forestry Centre, Sault Ste. Marie, ON
Michel Campagna, Gouvernement du Québec
Douglas Chan, Environment Canada
Jiaxin Chen, Government of Ontario
Jing M. Chen, University of Toronto
Steve Colombo, Government of Ontario
Nicholas Coops, The University of British Columbia
Carole Coursolle, Laval University
Anna Dabros, CFS, Ottawa, ON
Jeff Dechka, CFS, Pacific Forestry Centre, Victoria, BC
Bill de Groot, CFS, Great Lakes Forestry Centre, Sault Ste. Marie, ON
Raymond Desjardins, Agriculture and Agri-Food Canada
Dwayne Dye, Government of Saskatchewan
Caren Dymond, Government of British Columbia
Mike Flannigan, CFS, Northern Forestry Centre, Edmonton, AB
Rodney Foster, CFS, Atlantic Forestry Centre, Fredericton, NB
Sylvie Gauthier, CFS, Laurentian Forestry Centre, Québec, QC
Mark Gillis, CFS, Pacific Forestry Centre, Victoria, BC
Rory Gilsenan, CFS, Ottawa, ON
Martin Girardin, CFS, Laurentian Forestry Centre, Québec, QC
Jenny Gleeson, Government of Ontario
David Goodenough, CFS, Pacific Forestry Centre, Victoria, BC
Robert Grant, University of Alberta
Paul Gray, Government of Ontario
Ron Hall, CFS, Northern Forestry Centre, Edmonton, AB
Mark Hart, CFS, Ottawa, ON
Chris Hennigar, University of New Brunswick
Ted Hogg, CFS, Northern Forestry Centre, Edmonton, AB
Lin Huang, Environment Canada
Ryan Klos, Government of Manitoba
Werner Kurz, CFS, Pacific Forestry Centre, Victoria, BC
Tom Lakusta, Government of the Northwest Territories
Robert Landry, NRCan, CCRS, Ottawa, ON
Mike Lavigne, CFS, Atlantic Forestry Centre, Fredericton, NB
David Layzell, University of Calgary
Jacinthe Leclerc, CFS, Laurentian Forestry Centre, Québec, QC
Tony Lemprière, CFS, Ottawa, ON
Hank Margolis, Laval University
Dan McAskill, The Government of Prince Edward Island
Harry McCaughey, Queen's University
Dan McKenney, CFS, Great Lakes Forestry Centre, Sault Ste-Marie, ON
Mary Mes-Hartree, CFS, Ottawa, ON
Juha Metsaranta, CFS, Northern Forestry Centre, Edmonton, AB
Alison Munson, Laval University
Ray Nassar, Environment Canada
Vince Nealis, CFS, Pacific Forestry Centre, Victoria, BC
Aynslie Ogden, Government of Yukon
David Paré, CFS, Laurentian Forestry Centre, Québec, QC
Caroline Preston, CFS, Pacific Forestry Centre, Victoria, BC
David Price, CFS, Northern Forestry Centre, Edmonton, AB
Kirk Price, Government of Yukon
Eric Schroff, Government of Yukon
Brad Seely, The University of British Columbia
Marjorie Shepherd, Environment Canada
Walter Skinner, Environment Canada

Carolyn Smyth, CFS, Pacific Forestry Centre, Victoria, BC

David Spittlehouse, Government of British Columbia

John Stadt, Government of Alberta

Catherine Ste-Marie, CFS, Ottawa, ON

Graham Stinson, CFS, Pacific Forestry Centre, Victoria, BC

Kit Szeto, Environment Canada

Charles Tarnocai, Agriculture and Agri-Food Canada

Steve Taylor, CFS, Pacific Forestry Centre, Victoria, BC

Michael Ter-Mikaelian, Government of Ontario

Evelyne Thiffault, CFS, Laurentian Forestry Centre, Québec, QC

Brian Titus, CFS, Pacific Forestry Centre, Victoria, BC

Tony Trofymow, CFS, Pacific Forestry Centre, Victoria, BC

Shusen Wang, NRCan, CCRS, Ottawa, ON

Kara Webster, CFS, Great Lakes Forestry Centre, Sault Ste. Marie, ON

Clive Welham, The University of British Columbia

Jim Wood, CFS, Pacific Forestry Centre, Victoria, BC

Doug Worthy, Environment Canada

Evelynne Wrangler, Government of Alberta

Mike Wulder, CFS, Pacific Forestry Centre, Victoria, BC