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2023 Blueprint for Forest Carbon Science in Canada

Prepared by C. Smyth, J. Metsaranta, M. Fortin, S. Le Noble, H. MacDonald, J. Wolfe, C. Boisvenue, J. Laganière, J. Krakowski, X. Zhu, D. Paré, P. Tompalski, E. J. S. Emilson, K. Webster, M. Dosanjh, L. Venier, J. Edwards and based on input from the Canadian forest carbon science and policy communities.

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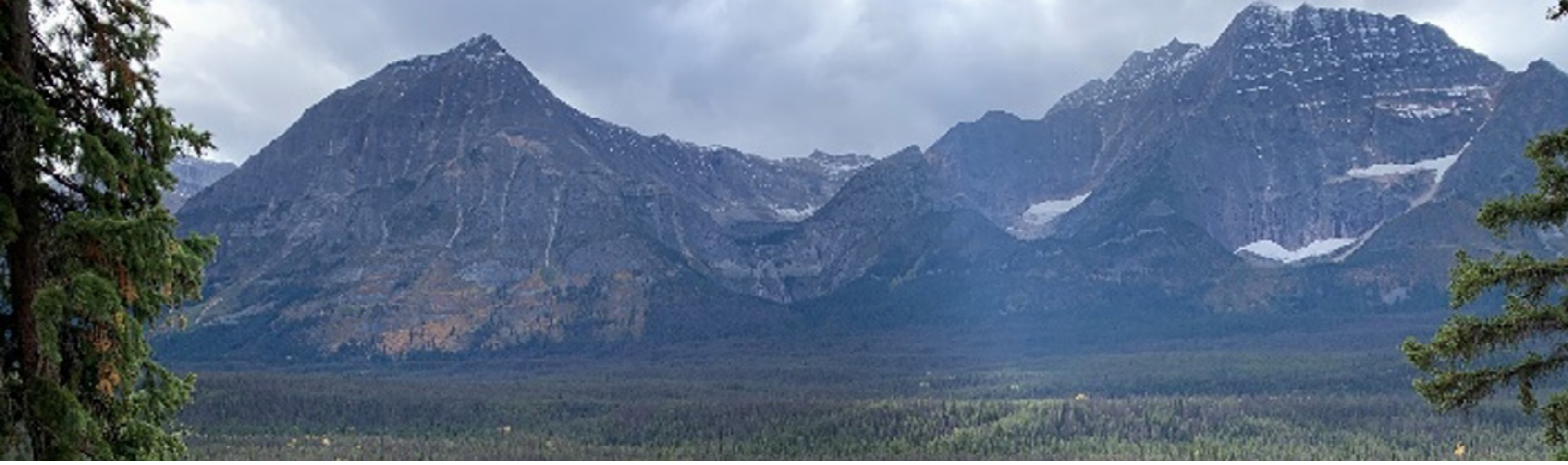

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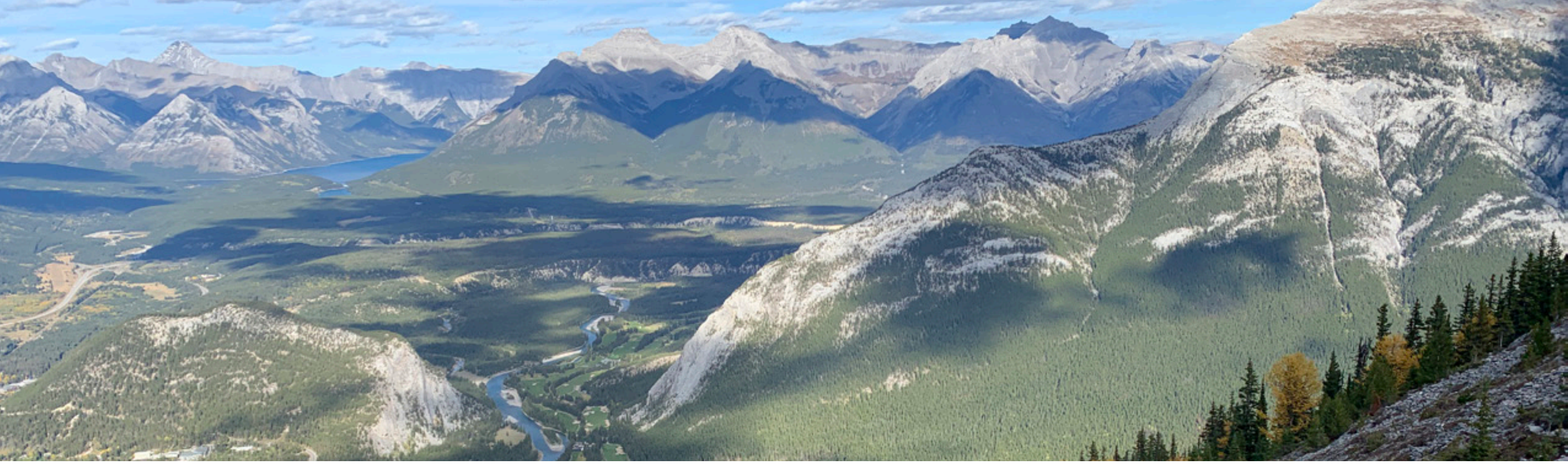

Land Acknowledgement

The authors respectfully recognize and acknowledge the relationship that the First Nations, Inuit, and Métis across Canada have with the land all Canadians live on and enjoy. We acknowledge that forest carbon research occurs on lands with which Indigenous Peoples have had a reciprocal relationship for millennia. We acknowledge the Indigenous Peoples on whose traditional territories the offices of the Canadian Forest Service, across the country, have the privilege to be situated. In particular, the department's headquarters in the National Capital Region are located on the traditional and unceded territory of the Algonquin Anishinaabeg people.

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This Blueprint is dedicated to the late Jason Edwards, whose leadership was instrumental in its development. Jason leaves a legacy at the Canadian Forest Service that will be remembered for many years to come.

Executive Summary

Forest carbon emerged as an important policy issue in Canada in the 1990s and has become an increasingly salient issue globally. Forests and wood products are included in Canada's climate change policy instruments (e.g., 2030 Emissions Reduction Plan) and commitments (e.g., reporting to the United Nations Framework Convention on Climate Change), and these require the best available science. Over the past few decades, scientific progress has been substantial and has contributed immensely to forest carbon policy, but considerable uncertainties remain, and policy needs are evolving.

This 2023 Blueprint for Forest Carbon Science in Canada (hereafter the Blueprint) provides an update to the 2012 Blueprint: A Blueprint for Forest Carbon Science in Canada: 2012–2020[1], and outlines forest carbon science priorities needed to support policy over the next decade. An understanding of policy-relevant science priorities will help funding organizations and the forest carbon science and policy communities to focus their resources and align their efforts.

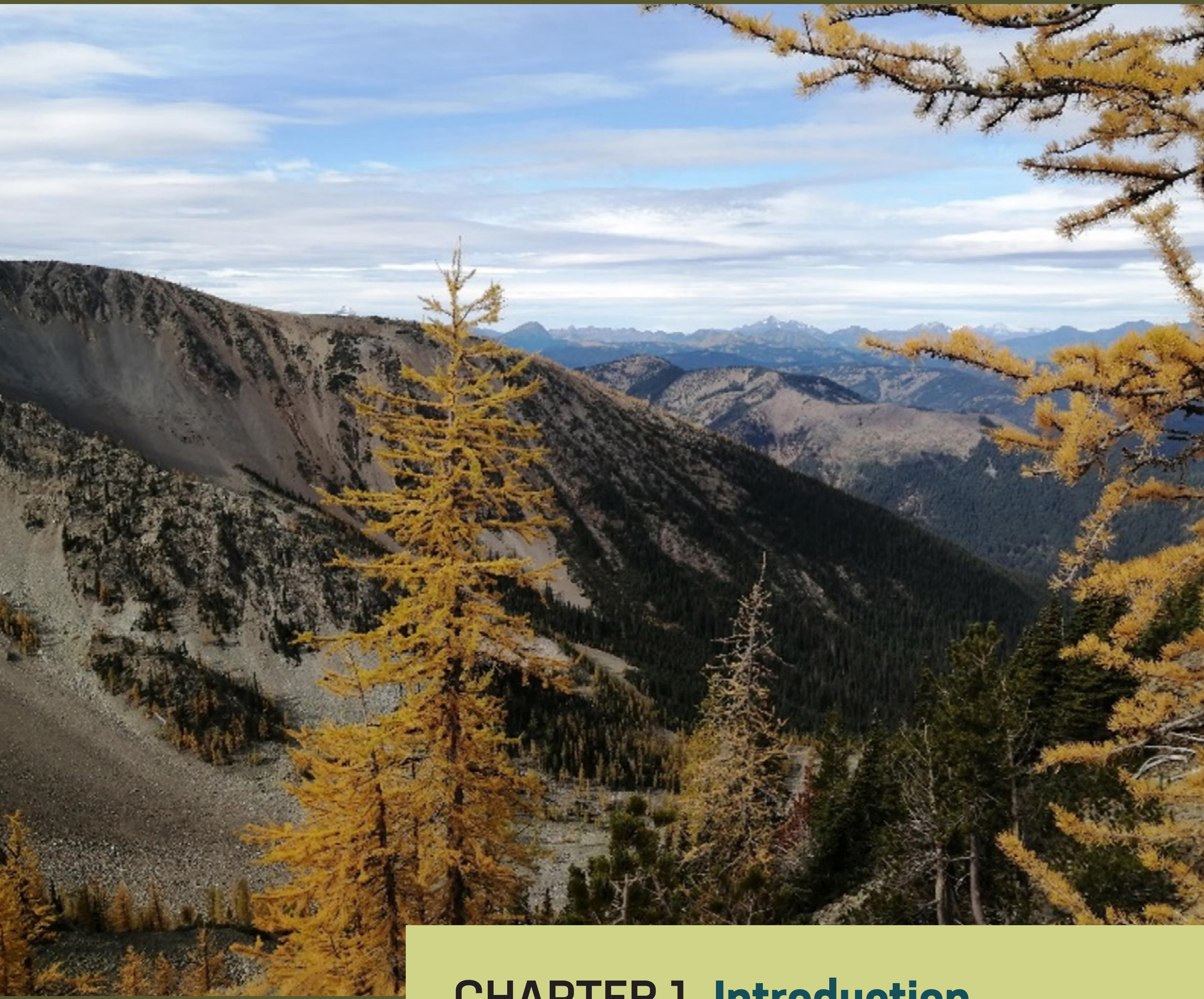
The Blueprint discusses five overarching forest carbon science-policy themes that are expected to be important for Canada over the next decade. Each theme includes key science goals to support policy development and improvement (Table EX 1) as well as future visions to guide overall efforts. The updated themes and science goals were developed in collaboration with the forest carbon science and policy communities across Canada. The increasingly complex, multifaceted, and evolving policy challenges in the face of climate change and other global crises require the support of sustained scientific research programs that are focused on informing policy decisions.

Regular reviews of the Blueprint are needed to ensure forest carbon science priorities continue to inform evolving policy priorities. Finally, in updating the Blueprint, it has become clear that this is an opportunity to bring in Indigenous Knowledge more fully, and to invite Indigenous working groups to provide leadership for collaborative carbon science opportunities and activities.

Table EX 1. Forest carbon science and policy themes, goals and vision.

Policy and Science Theme	Goal	Vision
Impact of human actions on forest sector carbon	1. Continuous improvement of national anthropogenic greenhouse gas (GHG) estimates for the forest and associated harvested wood products, including historical and projected estimates, and uncertainties.	To provide increasingly accurate estimates of anthropogenic forest and associated wood product emissions and their uncertainties, that are accessible to the public, proactively communicated, and broadly accepted.
	2. Improve understanding of the impacts of human activities such as forest management, land use change, and other industrial development on current and future carbon dynamics at site and landscape levels.	Continuous improvement in our estimates of the impacts of human activities on historical and projected forest carbon dynamics at a fine level of detail, which will improve forest sector GHG emission and mitigation estimates. Forest land managers and other stakeholders will have access to site- and landscape-level information on the impact of various human activities on current and future forest carbon dynamics.
	3. Improve spatially explicit modelling and monitoring to better estimate anthropogenic impacts on forest carbon and compare to global forest carbon estimates.	Canada will have a fully spatially explicit framework to better quantify anthropogenic impacts on forest carbon. A high spatial resolution will allow for increased accuracy of forest carbon estimates that are more easily verified and compared to global estimates.
	4. Expand knowledge on forest sector carbon estimates to meet evolving needs.	Canada will continue to be a leader in forest carbon science with a strong capacity to address forest carbon policy issues and analytical needs at multiple levels. Assessments with national coverage of anthropogenic forest sector GHG emissions estimates will expand to meet evolving domestic and international needs.
	5. Continuous improvement in modelling and forecasting systems to estimate forest-related GHG emissions associated with anthropogenic activities.	Anthropogenic GHG emission estimates and forecasts, and the associated uncertainty, will be produced by a system of open and transparent models and data that allows for regular testing, updates, and evaluation.
Impacts of environmental factors, climate change, and natural disturbances on forest carbon dynamics	6. Advance understanding of the processes driving forest growth and productivity.	Large-scale observational datasets of forest growth and productivity components will be expanded across forest types and ecozones and will include regular remeasurements. Models of annual forest growth will be developed that include biological factors integrated with environmental and climate drivers. Ensembles of models using different approaches (e.g., biometric, tree ring, and flux towers) will be developed that better predict forest productivity at the landscape level, and climate-sensitive growth models will be developed that better predict tree mortality, survivor increment, and tree recruitment.
	7. Advance understanding of the processes driving biomass turnover and decomposition.	A curated database of collections and analyses of soils, dead organic matter composition, and degradability with sufficient representation across key factors (forest and soil type, parent material, and climate) will be available. A thorough understanding will be developed about the role of soil composition, geochemistry, environmental controls, natural disturbances, and soil community biodiversity in controlling biomass turnover, decomposition rates, and soil carbon stabilization processes.
	8. Advance understanding of carbon cycling processes in peatland and permafrost soils.	Data for key model inputs and parameters (e.g., small-tree biomass growth, moss productivity, spatial extent of permafrost-affected organic and mineral soils) will be expanded, and methods will be available to estimate methane fluxes, using refined spatial layers of peatland types and the water table. An improved understanding will be developed about environmental drivers and carbon cycling in peatland and permafrost-affected soils, and their vulnerability to future climate.
	9. Advance understanding of carbon flows from terrestrial to aquatic systems.	Monitoring at long-term forest watershed studies will provide decadal measurements of lateral (riverine and groundwater) carbon export. Frameworks will be developed to track lateral carbon flows from uplands to aquatic systems at catchment scales that incorporate high-resolution digital elevation models to estimate hydrologic flows and subsequent carbon loss or accumulation within the landscape.
	10. Understand and predict changes in natural disturbance regimes in a changing climate, and impacts on carbon pools, transfers, and fluxes.	National assessments of disturbed area and severity by disturbance type will be developed and combined with models and field studies to assess impacts on carbon pools, transfers, and fluxes. Models of climate-sensitive disturbance occurrence and intensity will be developed that support long-term (multi-decadal) forecasting, and integrated models will be developed that quantify the impacts of individual disturbances and cumulative effects of multiple disturbances on carbon dynamics.

Policy and Science Theme	Goal	Vision
Climate change mitigation opportunities in the forest sector	11. Identify climate change mitigation opportunities involving forest management, including adaptation measures and natural disturbance management options.	Canada's climate change mitigation programs involving the forest sector will be supported by expanded comparative assessments of management options that are regionally differentiated, relative to a forward-looking baseline, and based on the best available data and methods for quantifying forest carbon at the tree, stand, and landscape level. Analyses will include impacts of climate change and future disturbance risks, sensitivity assessments, and adaptation and natural disturbance-based forest management.
	12. Identify climate change mitigation opportunities involving afforestation, reduced deforestation, restoration, and reclamation.	Assessments with national coverage of climate change mitigation for afforestation and avoided deforestation opportunities will be developed based on the best methods available for quantifying carbon accumulation. These assessments will be regionally differentiated and will include management to promote growth and mitigate loss and disturbance risk, in addition to including non-GHG impacts directly related to warming.
	13. Identify climate change mitigation opportunities involving wood products.	Assessments with national coverage of the climate change mitigation potential for wood use will be regionally differentiated, will consider all stages of a product's life cycle and substitution benefits, and will address some of the barriers to implementation.
	14. Identify climate change mitigation opportunities involving bioenergy.	National bioenergy GHG estimates and costs will be developed for a range of feedstock selections and regionally differentiated fossil energy assumptions. New tools will become available that use simple and practical methods for managing bioenergy projects that contribute to net-zero commitments, based on the best available data and methods.
	15. Develop forecasting systems and model linkages that permit evaluation of baseline and scenarios of mitigation and adaptation.	Progress towards mitigation and adaptation goals will be tracked using transparent, flexible, and nimble modelling systems that provide iterative spatially explicit forecasts of mitigation scenarios. Forecasts will be constantly updated and evaluated as new data and science become available and are integrated in the modelling system.
Indigenous perspectives and traditional knowledge	16. Improve understanding of forest carbon through Indigenous-led research that is centred on Indigenous voices and experiences and application of Indigenous Knowledge systems.	Truth and Reconciliation Commission (TRC) Calls to Action and Bill C-15 implementation will be reflected in forest carbon scientific research, bringing in Indigenous voices as an essential component and recognizing that Indigenous Knowledges and western approaches are both important, are both needed, and require significant changes to research practices and collaborations to be respectful to Indigenous Peoples and Indigenous methodologies. Understanding of Indigenous Methodologies, protocols, and knowledge in forest carbon research priorities, goals, and actions will be advanced through authentic and respectful Indigenous engagement with national Indigenous organizations, and under the guidance of Indigenous partners.
Connecting forest carbon to other values	17. Advance understanding of the broader impacts of Nature-based Solutions to climate change.	Forest carbon science will be integrated into well-balanced qualitative and quantitative evidence to advance the full range of Nature-based Solutions (NbS) benefits, including human well-being, clean water, and biodiversity. Forest carbon science will better reflect links between forest carbon and human well-being through a reconciliation lens.
	18. Advance interdisciplinary and multidisciplinary approaches to forest carbon science.	The forest carbon community will collaborate across disciplines to effectively and efficiently respond to emerging information needs and shifting expectations regarding other values, including commitments to Indigenous rights and reconciliation and biodiversity. Use of approaches that understand a range of values will enable multiple ways to implement forest carbon-based climate solutions.
	19. Improve communication of forest carbon modelling and research.	Forest carbon estimates and uncertainties, research findings, and information will be communicated in a way that meets the needs of Indigenous knowledge keepers, scientists, policy-makers, land managers, stakeholders, and the public.



CHAPTER 1. Introduction

1.1. Purpose of the Blueprint

In the past few decades, progress on forest carbon science has been substantial and has contributed to policy development[14]. Forest carbon emerged as an important policy issue in the 1990s and is an important issue globally, particularly due to its role in the climate system. The 2015 Paris Agreement[2] emphasized the need to curb increasing greenhouse gas (GHG) emissions to the atmosphere to hold "the increase in the global average temperature to well below 2° C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels." Many countries, including Canada, have considered the contribution from the land sector (commonly referred to as land use, land-use change, and forestry) towards national GHG reduction targets. Forests and wood products are included in Canada's climate change policy instruments (e.g., 2030 Emissions Reduction Plan) and commitments (e.g., reporting to the UNFCCC), and these require the best available science.

The purpose of the Blueprint is to outline forest carbon science contributions that will support evolving policy needs in Canada over the next 10 years. This is the second Blueprint: "A Blueprint for Forest Carbon Science in Canada: 2012-2020" was published in 2012 to guide policy and research aimed at filling regional, national, and international data gaps, and to support Canada's objectives and obligations for climate change mitigation and adaptation, sustainable forest management, and reporting requirements. Continuing that approach, the overarching forest carbon policy issues and science priorities in the Blueprint reflect national interests and priorities and include input from science and policy experts. It was developed with the understanding that implementation of the related content and recommendations are a shared responsibility.

The Blueprint recognizes and values Indigenous Knowledges both as independent and complementary to western science in understanding forest carbon with equally challenging needs and priorities. Indigenous Knowledges are equally valid and essential to developing forest and other nature-based solutions. A suitable space to share Indigenous teachings and knowledge would ensure leadership for collaborative opportunities and activities.

The Blueprint discusses

- the overarching forest carbon policy and science issues that are expected to be important for governments and the forest sector,
- the forest carbon science goals expected to provide the greatest support for policy,
- the approaches and partnerships needed to make progress in addressing these science priorities, and
- recognition and support of Indigenous perspectives and knowledge within forest carbon science.

The primary audience of the Blueprint is the forest carbon science community. The knowledge generated from the proposed science priorities will benefit governments, forest industry, environmental organizations, Indigenous organizations, and others in Canada who are interested in how forest management can be improved and how wood can be better utilized to maintain or enhance carbon storage; increase carbon removals from the atmosphere; and reduce GHG emissions to the atmosphere. Agreement on policy-relevant science priorities will help researchers, managers, and funding organizations focus their resources, align efforts, and inform the path towards meeting Canada's climate targets.

To engage the broader forest carbon community, several workshops and other focused discussions were held with representatives from federal, provincial, and territorial governments, forest industry, environmental organizations, and Indigenous organizations to identify key research goals, and a draft of this document was circulated for comment. At each stage, all comments were carefully considered to make this document as reflective as possible of the broad and diverse views on forest carbon science priorities. A summary of the process used to develop this document follows (see Box 1). During the development of this document, views were sought across the range of scientific disciplines and organizations. The input of the contributors (see Appendix 1) has helped ensure that the Blueprint comprehensively addresses forest carbon science and its relation to forest carbon policy in Canada. However, we acknowledge that additional contributions are needed and that there has been limited engagement with national Indigenous organizations.

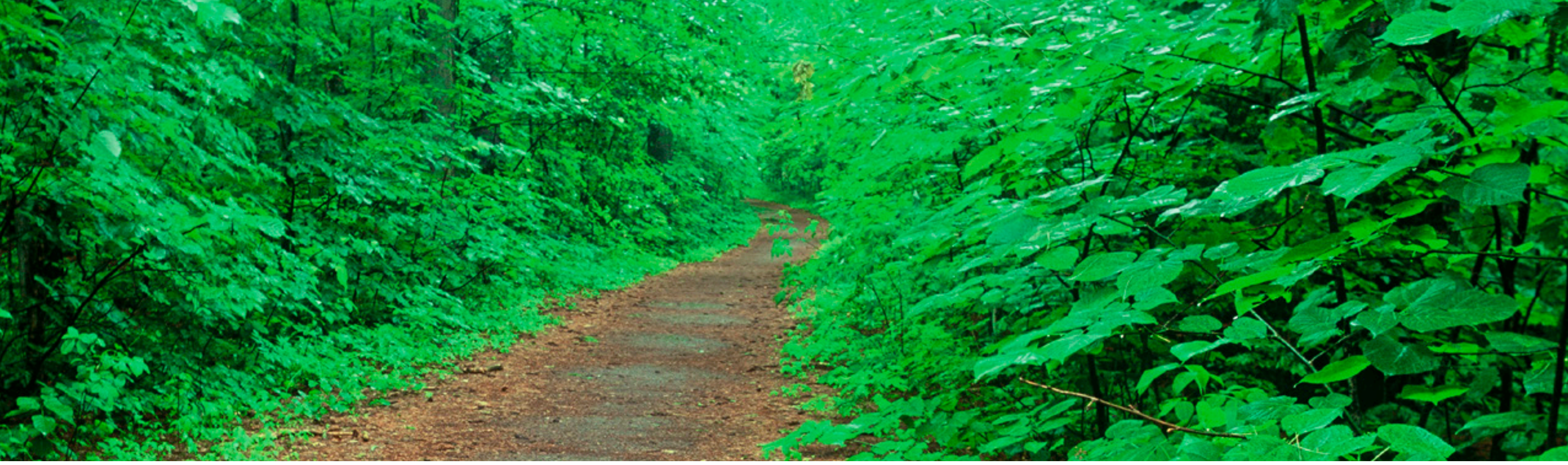
Regular reviews of this Blueprint are needed to ensure forest carbon science priorities continue to inform evolving policy priorities. For example, forest carbon-related policy and program goals are realigning more often as all levels of governments are called on to quickly respond to climate change. The process to review the Blueprint also provides the opportunity for increased collaboration among the forest carbon community as well as across interacting energy and materials sectors.

BOX 1: A summary of the process used to develop this document.

Developing the 2023 Blueprint for Canadian Forest Carbon Science

The blueprint is a product of focused collaboration among the forest carbon community.

- October 2022—A summary report on progress to date, with accompanying references, was circulated to Canadian Forest Service (CFS) researchers and policy advisors, along with a survey to assess progress to date on each of the 29 research goals identified in the 2012 Blueprint.
- November 2022—At a virtual workshop, over 60 CFS participants discussed progress over the past decade and delineated key forest carbon issues, considering both scientific and policy perspectives.
- February to April 2023—Updated goals were generated and discussed at a workshop with over 140 participants comprised of academic, industry, environmental organizations, Indigenous, and government experts who filled out a survey and provided comments to inform the Blueprint.
- June to September 2023—A draft of the revised Blueprint was sent for review to interested workshop participants and federal government experts for comments.



1.2. Context of Canada's Forests, Forest Governance, and Carbon

Canada's forests offer significant environmental, social, and cultural benefits and are a renewable source of timber, bioenergy, and other goods and services. For millennia, Canada's forests have been part of a larger reciprocal relationship between Indigenous Peoples and the land, and are intrinsically linked to the health, livelihoods, and well-being of Indigenous Peoples. Canada's forests provide habitat for many of Canada's terrestrial plant and animal species and constitute 10% of the world's forest cover and 30% of its boreal forest[3]. Forest land covers 362 million ha (roughly 40%) of Canada's land area and more than 75% of forest area is within the boreal zone. This zone also contains other ecosystem types and land covers, including peatlands, grasslands, lakes, wetlands, and tundra. Roughly 226 million ha of Canada's forests are managed for timber and nontimber resources (including parks and forest land subject to fire protection).

Canada has made a commitment to sustainable forest management, managing forests according to the principles of sustainable development which balance ecological, economic, and socio-cultural values. Sustainable forest management maintains and enhances 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[4]. The federal, provincial, and territorial governments each have a variety of policy goals related to forests in the context of their own jurisdictional responsibilities to guide and enforce sustainable forest management practices and standards on public and private lands across the country. Most of Canada's forest land is publicly owned and under provincial or territorial jurisdiction (88%) or federal jurisdiction (2%). The remaining forest land (10%) is privately owned or administered by Indigenous Nations[3].

Multiple jurisdictions have established goals for managing forests within Canada. Provincial and territorial governments have constitutional authority over the conservation and management of provincial and territorial lands. In addition to managing some forest lands, the federal government has responsibility for the national economy, trade, and international relations, of which the forest sector is an important element. Within the federal government, the Canadian Forest Service provides science and policy expertise and advice on national forest sector issues and publishes an annual report on the State of Canada's Forests[3]. The forest industry has forest management responsibilities through legal arrangements with provincial and territorial governments. Private forest owners, whether they are small woodlot owners or 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, to maintenance and conservation of ecosystems and the services they provide, one of which is carbon storage.

Forests interact dynamically with the atmosphere through massive exchanges of energy, water, and carbon that affect the earth's energy balance and climate. Canada's forests are important in the global carbon cycle because of their size and because they contain vast quantities of carbon stored in vegetation, deadwood, organic and mineral soils, peatland, permafrost, and carbon derived from forests in aquatic and marine systems. Our forests can emit carbon or remove carbon from the atmosphere depending on the net balance of large fluxes between the atmosphere and the forest, wood use emissions, and forest conversion (See Box 2 and NIR2023[5]).

BOX 2: An integrated system to estimate Canada's forest sector emissions and removals.

Canada's historical and projected forest sector GHG estimates are generated by Canada's National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS)[6–8]. Historical results are published in annual National GHG Inventory Reports to the United Nations Framework Convention on Climate Change (UNFCCC), and these reports have included forest carbon estimates for many years[5]. Canada's historical forest sector GHG estimates are also published in annual State of the Forest reports as well as in several provincial GHG reports and climate action plans. Projected forest sector GHG estimates are published in Biennial Reports to the UNFCCC as well as in Canada's domestic emissions projection reports, climate plans, and progress reports[9]. These reports show the contribution of the forest sector, relative to other economic sectors, towards meeting Canada's climate targets.

As trees grow, they absorb carbon from the atmosphere, some of which is stored in vegetation (biomass), dead organic matter, and soils. Carbon is returned to the atmosphere through respiration and the decay and burning of organic matter. Net carbon uptake is influenced by management practices and natural disturbances, both in the immediate and long term. Disturbances cause mortality, which increases emissions as wood decomposes. Post-disturbance regeneration creates young forests, which initially have low carbon uptake rates. In Canada, natural disturbances can cause large interannual variability in emissions from year to year, depending on large variations in the area affected by wildfire and pests. In keeping with international guidelines[16], Canada disaggregates emissions and removals from managed forest lands into lands recently affected by significant natural disturbances (e.g., wildfires and pests) and lands affected by human (anthropogenic) activities such as harvesting and planting.

Forest harvesting transfers carbon to harvested wood products (HWP) and produces harvest residues (branches, foliage, and non-commercial species) which are left to decay or are burned. The combination of emissions and removals from forests and emissions from wood products harvested from the forest represents the net flux between managed forests and the atmosphere.

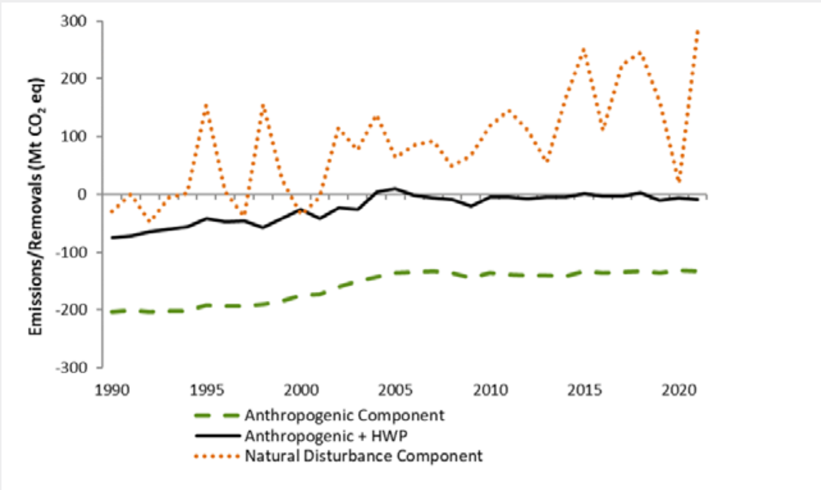


Figure Box 2: Emissions and removals from Canada's managed forest are reported annually[5] and are disaggregated into contributions from forest lands affected by anthropogenic impacts (dashed green line), for example harvesting and planting, and those from lands affected by natural disturbances (dotted orange line) that are outside of human control. Emissions from wood that is harvested and converted to products and energy and released back to the atmosphere are added to the anthropogenic component and reflects the emissions and removals from the forest and harvested wood products (HWP) (solid black line).

NFCMARS operates under a continuous improvement plan[10] which is published annually and identifies improvements in processes, data, and model parameters. Proposed updates to the system will result in important changes in the reported carbon emissions that occur in Canada's managed forest. A second-generation version of this system is envisioned for monitoring carbon in the forest and in harvested wood products that will be spatially explicit with high spatial resolution. This system will quantify the impacts of human activities with reduced uncertainty, expand forest carbon budget analyses to Canada's entire forest area, and integrate forest emissions and removals into larger-scale assessments of carbon fluxes.

It is increasingly recognized through scientific studies and observed intensification of natural disturbances that feedbacks between climate and losses from long-lasting terrestrial carbon pools[11] may profoundly alter the trajectory of future atmospheric GHG concentrations and climate change. 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. 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[12] and exceed emission reductions achieved in all other sectors[9]. The question of how Canada's forest carbon budget for managed and unmanaged forests will respond to global climate change has scientific, environmental, social, and policy relevance in adapting and maintaining healthy ecosystems, human societies, and future mitigation efforts.

1.3. Scope and Structure of the Blueprint

The scope of this Blueprint includes policy-relevant carbon science related to forest ecosystems and the forest sector, lifting up Indigenous voices, connecting carbon to other values, and improving communication and science-policy integration. Policy decisions around carbon management will need to consider many other goals of sustainable forest management, such as those related to biodiversity, climate change adaptation, economics, water quality and quantity, and human well-being, among others, but the focus of the Blueprint is foremost on forest carbon.

In this report, carbon refers to carbon dioxide (CO_2) and other climate-relevant non-CO_2 GHGs such as methane and nitrous oxide, where applicable. Emissions refer to a source of carbon released into the atmosphere, and removals refer to removing carbon from the atmosphere (carbon sink). The forest sector is the combination of forests and forestry industries that produce harvested wood products (including bioenergy), and thus forest sector carbon includes forest ecosystem and wood product carbon emissions.

The next ten years will bring changes to our understanding of forest sector carbon, including improvements in quantifying emissions and removals in managed and unmanaged forest ecosystems in Canada, emissions from harvested wood products including bioenergy, and emissions in interacting product and energy sectors for GHG reduction analyses. Scientific research will take a broader landscape perspective to account for the important role that peatlands, linkages between upland, peatland, and aquatic ecosystems, and permafrost-affected lands have on regional, national, and global carbon cycles[13].

This document consists of an executive summary and three chapters, including this introductory Chapter 1. Chapter 2 describes the five overarching forest carbon policy and science themes and their key research goals. Chapter 3, the conclusion, discusses knowledge exchange efforts required to ensure the Blueprint continues to be an effective science-policy integration tool.

1.4. Progress to Date and What We Have Heard

The 2012 Blueprint identified four key policy themes, four science themes, and ten questions that guided activities for research organizations and supported policy development. In the ten years since it was published, a substantial body of forest carbon research relevant to Canada has resulted, and many studies have been undertaken by federal departments, agencies, provinces and territories, external organizations, and through partnerships to answer the research questions posed in the Blueprint. Canada's forest carbon scientific research substantially advanced the understanding of the current and anticipated emissions and removals in the forest sector, the processes that influence them, and the contribution of Canada's forests to the global carbon cycle. Progress has also been made in understanding the range of mitigation options to reduce forest sector GHG emissions and/or increase carbon removals in forest ecosystems.

In 2022, CFS conducted a review of peer-reviewed published literature for scientific articles relevant to the 2012 Blueprint research questions[14]. A summary of the number of publications and associated citations was presented at a series of workshops with the Canadian forest carbon community in 2022 and 2023, along with workshop participant responses to a survey which gauged how much research progress had been made over the past 10 years. A summary comparison shows good agreement between the survey responses and literature review (see Appendix 2). The literature review revealed that most of the publications since 2012 focused on quantifying current forest carbon emissions and on estimating the climate change mitigation potential of the forest sector. Survey responses noted moderate to major progress in many areas, with less progress noted for assessing the impacts of Canada's forest on the global climate system, which had fewer publications.

Workshop participants suggested that future literature reviews could be more inclusive of other types of knowledge besides peer-reviewed publications. They also noted that the literature review increased their understanding of progress to date, and that some research questions had been partly addressed by publications, but gaps remained. Participants raised the topic of uncertainties involved in forest carbon modelling, and many comments were provided on data (availability, quality, consistency, scalability, standards, appropriate scales, and integrating more diverse sources) and models (incorporating empirical, process, and mechanistic components, linking to non-GHG models, testing, validating, assessing sensitivity, and ensemble modelling). Additional comments from workshop participants suggested that new research themes were needed to highlight Indigenous voices in the Blueprint, and to address synthesis activities and platforms to facilitate knowledge sharing and collaborative interdisciplinary research. These new themes would enable research to span the diversity of ecosystems and forest sector attributes across Canada required to address the rapidly changing impacts of climate change and incorporate this information into mitigation and policy efforts at appropriate scales.

CHAPTER 2. Forest Sector Carbon Policy and Science Themes

The five science-policy themes for the Blueprint are:

1. Impact of human actions on forest sector carbon
2. Impacts of environmental factors, climate change, and natural disturbances on forest carbon dynamics
3. Climate change mitigation opportunities in the forest sector
4. Indigenous perspectives and traditional knowledge
5. Connecting forest carbon to other values

The first three themes relate to forest carbon estimation, foundational forest science research, and climate change mitigation and are like those found in the 2012 Blueprint. Themes four and five are new themes that were developed based on recommendations from the forest carbon community to include a focus on storytelling and centering Indigenous voices to improve policy and program outcomes, and to include more social, economic, environmental, and cultural dimensions (see also Box 3). Themes are numbered for readability but are not ranked.

The five science-policy themes and their related research goals address the improvements in understanding and information required over the next decade to satisfy information needs of policy-makers. The research goals are determined based on the current understanding of the processes driving forest sector GHG emissions and removals, sources of uncertainty, knowledge gaps, and vulnerability of processes to changes in environmental conditions, considerations of current biodiversity and sustainability goals, and current modelling and computing capacities.

BOX 3: Models and modelling systems.

Forests are complex and dynamic systems, and carbon cycling is an emergent property of forests that cannot be easily measured directly. Instead, models are used to simulate the carbon dynamics of forests. Across all five Blueprint themes, improved modelling is needed to connect forest carbon to other values, accelerate science and methodological uptake, and improve science-policy integration.

Approaches to mitigate climate change, conserve biodiversity, and maintain human well-being will require modelling efforts that are based on a holistic view to support a diverse, complementary suite of solutions. For example, forest carbon models could also include biodiversity indicators, climate sensitivity, and other linkages, working towards a complete representation of dynamics on the landscape, to better inform policy development in the face of multiple, competing global crises.

Developing multi-value models that are robust, transparent, and easier to update will ensure decision makers have rapid access to the best available science, even as new data, perspectives, and complex relationships arise. Models can be improved by following guiding principles of predicting frequently, evaluating our models, and making them reusable, freely available, interoperable, built using continuous workflows, and constantly tested[15]. Policy decisions will be better informed and communication with the public will be more transparent with better knowledge of the uncertainty in predictions and assessments, including model estimate uncertainty.

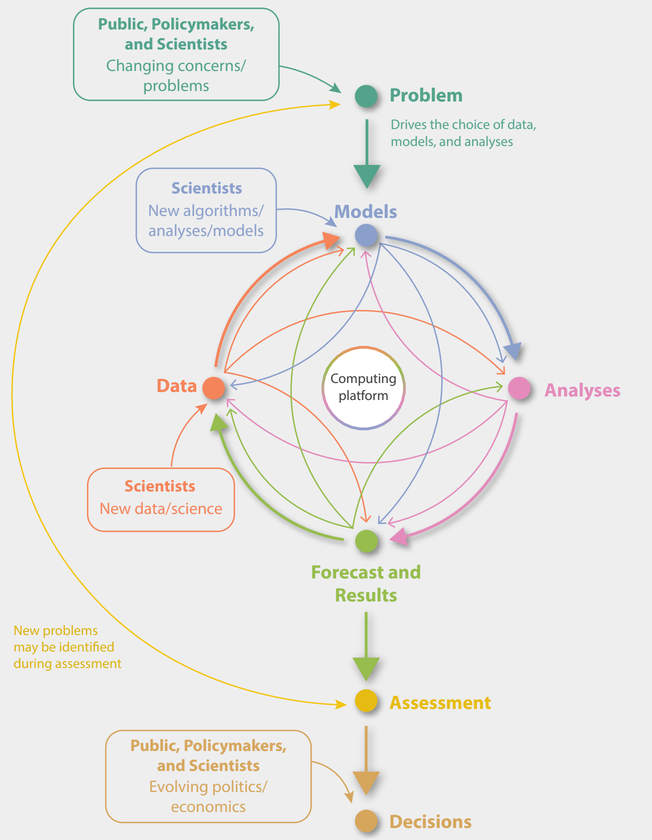


Figure Box 3: Modelling efforts are needed that support a diverse suite of solutions. Robust multi-value models that are easy to update will ensure decision makers have rapid access to the best available science.

Theme 1. Impact of human actions on forest sector carbon

The United Nations Framework Convention on Climate Change (UNFCCC) sets the overall framework for international efforts to tackle climate change. Under the UNFCCC framework, Canada committed to reduce anthropogenic emissions by 40–45% below 2005 levels by 2030 and achieve net-zero emissions by 2050. As part of this commitment, Canada is required to transparently report and continuously improve economy-wide estimates of anthropogenic (human-caused) GHG emissions and removals, including for forests and wood products over the historical period (generally 1990 onwards).

Efforts to improve and enhance Canada's national reporting framework are underway (see Box 2), and the forest carbon science goals identified in this theme will increase the capacity to address policy issues and analytical needs at multiple levels. Forest carbon science has effectively informed Canada's position in international climate change negotiations over many years, and the need to prioritize science- and evidence-based decisions will continue as international discussions progress over the next decade.

GOAL 1: Continuous improvement of national anthropogenic GHG estimates for the forest and associated harvested wood products, including historical and projected estimates, and uncertainties.

To remain a reliable source of information on Canada's forest sector GHG emissions, the science-policy community needs to regularly report transparent, verifiable estimates and projections and their uncertainties. These reported values will change as science progresses to reflect our improved understanding but will continue to aim to be accurate (neither systematically overestimating nor underestimating the true emissions or removals, so far as can be judged) and precise as far as practicable[16]. Scientific improvements will change the size of the estimated emissions, and maybe even the sign of the emissions (i.e., switching from removing carbon from the atmosphere to emitting carbon), and will also affect the uncertainty of the estimates.

There is a need to clearly communicate Canada's efforts, not only to fulfill reporting requirements, but also in the public sphere to ensure transparency and confidence. This could include additional ways of expressing estimates of forest carbon emissions and removals, or providing information on metrics in addition to those required for international reporting. Broad acceptance of improved results could be challenging, and better communication using two-way communication strategies and clear descriptions of limitations and uncertainties in Canada's forest carbon estimates will improve trust (see Theme 5).

Vision: To provide increasingly accurate estimates of anthropogenic forest and associated wood product emissions and their uncertainties that are publicly accessible, proactively communicated, and broadly accepted.

GOAL 2: Improve understanding of the impacts of human activities such as forest management, land use change, and other industrial development on current and future carbon dynamics at site and landscape levels.

Forest management, land-use change, and other industrial development can emit carbon from forest and peatland ecosystems into the atmosphere, transfer carbon to harvested wood products, redistribute carbon within ecosystems, and influence the future forest carbon trajectory of the ecosystem. The representation of these impacts at site and landscape levels influences estimates of anthropogenic GHG emissions and mitigation potential.

Impacts of forest management activities on forest carbon need to be better understood at site- and landscape levels for all carbon pools (aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter) in forest ecosystems, including peatlands. The influence of site preparation on soil carbon, improved representation of harvesting approaches with various retention levels, the impact of thinning (commercial and pre-commercial) on carbon stocks and subsequent growth, impacts of harvesting on uneven-aged stands, and initial soil carbon estimates for afforestation or reforestation sites are examples of human activities where improved understanding is required. Including

Indigenous history and knowledge of the land can also improve our understanding of emissions and removals as well as mitigation estimates. Human activities can also have a negative influence, resulting in forest degradation, and improved understanding about where and how human activities may have degraded forests is also required.

Vision: Continuous improvement in our estimates of the impacts of human activities on historical and projected forest carbon dynamics at a fine level of detail, which will improve forest sector GHG emission and mitigation estimates. Forest land managers and other stakeholders will have access to site- and landscape-level information on the impact of various human activities on current and future forest carbon dynamics.

GOAL 3: Improve spatially explicit modelling and monitoring to better estimate anthropogenic impacts on forest carbon and compare to global forest carbon estimates.

Availability of remotely sensed data and algorithms to process them have rapidly evolved in recent years. New sensors and datasets are expected to become available soon, which will allow for more accurate forest inventory characteristics and will better characterize forest management activities through land cover change assessments. By using these datasets in spatially explicit forest carbon models, better estimates of GHG impacts of forest management, afforestation, and deforestation impacts will be possible. In addition, georeferenced information will enable remote monitoring to ascertain the successful implementation of forest carbon-related programs and policies.

Multiple remote sensing datasets are available with differing coverage, resolution, and data type (e.g., airborne laser scanning, Landsat time series) that are processed at local, national, and global scales. These datasets are crucial for improved monitoring and modelling of GHG emissions and are important for comparisons to global assessments.

Vision: Canada will have fully spatially explicit framework to better quantify anthropogenic impacts on forest carbon. A high spatial resolution will allow for increased accuracy of forest carbon estimates that are more easily verified and compared to global estimates.

GOAL 4: Expand knowledge on forest sector carbon estimates to meet evolving needs.

Canada has established international commitments that intersect with forest carbon issues, such as signing onto the Glasgow Leaders' Declaration on Forests and Land Use to halt and reverse forest loss and land degradation globally. In addition, there have been requests from Canadians and trading partners for more in-depth information. These requests provide opportunities to increase openness and transparency by providing additional information on anthropogenic activities in all of Canada's forests, and promote a more complete, shared understanding of sustainable forest management performance and climate mitigation services provided by Canada's forests. Thus, new assessments with national coverage need to be designed and implemented, expanding on our current systems by including additional processes such as climate sensitivity, impacts related to degradation, and quantifying complete sector emissions (e.g., supply chain, radiative impacts, and aquatic carbon flows) and interactions with other sectors of the economy.

Vision: Canada will continue to be a leader in forest carbon science with a strong capacity to address forest carbon policy issues and analytical needs at multiple levels. Assessments with national coverage of anthropogenic forest sector GHG emissions estimates will expand to meet evolving domestic and international needs.

GOAL 5: Continuous improvement in modelling and forecasting systems to estimate forest-related GHG emissions associated with anthropogenic activities.

Modelling frameworks for reporting and research on anthropogenic GHG emissions and removals will need to enable continuous science improvements, data testing, and updates of estimates and associated uncertainties. Frameworks will include open and transparent models that are flexible and interoperable with modelling frameworks that assess natural impacts on GHG emissions (Theme 2), allow for assessment of mitigation opportunities and baselines (Theme 3), and that are interoperable with models that allow carbon and other values to be assessed together in interdisciplinary assessments (Theme 5). The frameworks will include a continuous workflow from data to simulation and will increase the availability and transparency of data related to GHG estimates.

Vision: Anthropogenic GHG emission estimates and forecasts, and the associated uncertainty, will be produced by a system of open and transparent models and data that allows for regular testing, updates, and evaluation.

Theme 2. Impacts of environmental factors, climate change, and natural disturbances on forest carbon dynamics

In general, this theme underscores the importance of foundational research on forest ecosystem processes to enable the advancement of applied forest carbon research with direct policy relevance. Much progress has been made over the past decade to enhance our foundational understanding of forest carbon dynamics; however, not all processes are quantified, nor are their interactions consistent across scales. There is significant uncertainty in future forest carbon growth and decay due to changing climatic and environmental conditions, and the limited understanding of the interactions between disturbance factors and these processes. We need to better understand future changes and uncertainty to increase the accuracy of retrospective and predictive models, for both managed and unmanaged forests. The foundational nature of this theme also lends to its relevance to UNFCCC reporting requirements (see Theme 1) and measuring and communicating impacts of policies and programs aiming to mitigate and adapt to climate change (see Themes 3 and 5).

Predicting future forest carbon dynamics will require enhanced understanding of ecosystem processes driving the balance between carbon uptake through growth and productivity and carbon release through respiration and leaching into aquatic systems. Expanding the forest carbon budget to include peatland and aquatic systems embedded within forests as well as carbon transfers among the systems is key to building a more comprehensive view of forest responses to change[13]. Climate change is affecting Canadian forests; more data and long-term scientific studies of carbon fluxes are essential to increase our understanding of environmental change impacts on biophysical processes of forest ecosystems. This includes the need for understanding regional variations in both carbon processes and their responses to climate change. Enhanced datasets and derived spatial products (see Appendix 3) are essential for understanding trends, informing model predictions, and supporting policy development to address climate change impacts[17,18].

GOAL 6: Advance understanding of the processes driving forest growth and productivity.

Annual forest productivity is the main pathway for removing carbon dioxide from the atmosphere through the process of photosynthesis. In terrestrial ecosystems, trees take carbon from the atmosphere through photosynthesis and consume a portion for their own metabolism. The amount of fixed carbon that remains is called the net primary production (NPP), and includes new tree growth, as well as annual turnover of trees or tree components (foliage, branches, and fine roots).

Estimating NPP is challenging, even though methods for field estimation are known[19] due to the vast extent and remoteness of Canada's forests, and because many of the components of NPP are difficult to measure. Several initiatives have been undertaken with the objective of collecting more data and making them accessible. The National Forest Inventory (NFI) program compiles data on various forest attributes, including biomass pools at permanent ground sampling plots as part of its inventory protocol. While the NFI has a limited number of ground plots, the data are invaluable as they capture information from all forested ecozones in Canada. The MAGPlot database was created with the aim of harmonizing the provincial and territorial permanent and temporary sample plot datasets, and the CFS-TRenD database contains extensive tree-ring observations from forest ecosystems across Canada (Appendix 3).

This significant effort directed towards understanding aboveground biomass (or, alternatively, wood volume) increment, even though it is a small component of NPP, is because of the importance of the wood products industry and because it is easier to measure than litterfall or root growth and turnover. Carbon uptake based on modelling techniques for Canada's managed forest showed that most NPP is directed towards replacement of foliage and fine root turnover rather than net biomass increment[20]. Litter input and its subsequent decomposition is a major pathway for organic matter input to forest soils and has a strong influence on forest productivity and soil nutrient status, as discussed in the next goal.

Advancing our understanding of the key processes driving climate sensitivity of forest growth and productivity will improve our predictions of carbon uptake by our forests and how it will be affected by the future climate. Effective policies require climate-sensitive growth models for predicting future carbon emissions and removals in the forest-wood product chain, but many of the growth models that support sustainable forest management decision-making in Canada currently lack climate sensitivity impacts. Climate-sensitive process-based models (e.g., BEPS, Triplex, 3PG), which aim to reflect climate fluctuations in biomass growth, have also been used in some provinces and territories to predict carbon emissions and removals. Several initiatives are underway to develop climate-sensitive growth models or to add climate modifiers to current empirical growth models but they are not widely available or have not been thoroughly tested.

Vision: Large-scale observational datasets of forest growth and productivity components will be expanded across forest types and ecozones and will include regular remeasurements. Models of annual forest growth will be developed that include biological factors integrated with environmental and climate drivers. Ensembles of models using different approaches (e.g., biometric, tree ring, and flux towers) will be developed that better predict forest productivity at the landscape level, and climate-sensitive growth models will be developed that better predict tree mortality, survivor increment, and tree recruitment.

GOAL 7: Advance understanding of the processes driving biomass turnover and decomposition.

Soils are the largest terrestrial storehouse of carbon. Carbon is emitted to the atmosphere through respiration originating from roots and from decomposition of dead organic matter (DOM), composed of coarse woody debris, litter (dead roots and leaves), and soil pools. Advancing our understanding of the processes that drive biomass turnover and decomposition will improve our predictions of carbon emissions and impacts of the future climate on carbon storage in forests.

Decomposition processes can be affected by changes in climate, as they are sensitive to temperature and moisture conditions as well as nutrient levels. Over the last two decades, measurements of soil organic matter and woody debris have been incorporated into the NFI, and other soil databases have been curated and harmonized[21]. This has allowed digital soil mapping of soil carbon and other soil properties at local to regional to national scales to be improved. However, estimates are still coarse because data are lacking, particularly soil carbon observations at depth where significant stores lie[22], and yet these data are essential for modelling stocks and fluxes.

Recent scientific research has pointed to the importance of vegetation composition, natural disturbances (wildfire, pests, etc.), and soil fauna biodiversity on soil and woody debris characteristics, susceptibility to decay, and rates of carbon fluxes. Physiochemical processes controlled by hydrology, weathering, and parent material further control soil carbon stores through organo-mineral interactions that stabilize carbon within mineral soils. However, additional process-based studies are required to understand how physical, biological, and chemical mechanisms interact to determine decomposition, leaching, and erosion rates and their sensitivity to a changing climate. While some direct measurements of these rates have been carried out using field-based methods (e.g., CIDET, a 12-year litterbag decomposition experiment or eddy covariance studies), the data available from long-term studies or monitoring programs across ecozones for model calibration and validation have been limited.

Vision: A curated database of collections and analyses of soils, dead organic matter composition, and degradability with sufficient representation across key factors (forest and soil type, parent material, and climate) will be available. A thorough understanding will be developed about the role of soil composition, geochemistry, environmental controls, natural disturbances, and soil community biodiversity in controlling biomass turnover, decomposition rates, and soil carbon stabilization processes.

GOAL 8: Advance understanding of carbon cycling processes in peatland and permafrost soils.

Forested landscapes are a mosaic of upland forests, lowland forests, and wetlands, including peatlands such as open, treed and forested bogs, poor fens, and rich fens. In more northerly ecozones permafrost-affected soil can also exist in peatland and mineral soils. Advancing our understanding of carbon cycling processes in peatland and permafrost soils that are carbon rich and climate-vulnerable will better allow us to predict the impacts these critical components have on national carbon emissions and removals. Thick organic layers occur because of long-term accumulation of carbon under cold and/or anoxic conditions. There has been greater international pressure to report on emissions and removals of carbon from these systems given the large storage of carbon which may decompose as climate warms.

Modelling carbon dynamics in these systems is a highly complex and uncertain exercise. Over the last decade, efforts have improved national-scale peatland mapping, developed peat property databases (e.g., peat depth, carbon and nutrient concentrations), derived peatland-specific biomass functions, and collated methane and net ecosystem exchange observations from across peatlands for model development[23]. These efforts led to the creation of a moss model (MOSS-C) for use on mineral soils with thick organic layers[24] and the Canadian Model for Peatlands (CaMP) was developed to run as modules within the Generic Carbon Budget Model

(GCBM). The CaMP has been applied across major peatland-containing ecozones where permafrost is not present, to simulate GHG emissions and removals and net ecosystem and biome productivity[25].

Vision: Data for key model inputs and parameters (e.g., small-tree biomass growth, moss productivity, spatial extent of permafrost-affected organic and mineral soils) will be expanded, and methods will be available to estimate methane fluxes using refined spatial layers of peatland types and the water table. An improved understanding will be developed about environmental drivers and carbon cycling in peatland and permafrost-affected soils, and their vulnerability to future climate.

GOAL 9: Advance understanding of carbon flows from terrestrial to aquatic systems.

Carbon that is sequestered within the forest does not always remain in the forest—some carbon is emitted back to the atmosphere, and a portion is transported as dissolved fluxes of inorganic and organic carbon. These fluxes are referred to as "lateral" because they go from the forest to wetlands, streams, rivers, and/or lakes or coastal marine systems, where they are eventually stored in sediments or emitted back to the atmosphere. Magnitude and controls on lateral carbon fluxes, and the cycling and fate of forest-derived carbon in inland freshwater ecosystems have been identified as important knowledge gaps in global carbon accounting models.

Advancing our understanding of carbon flows from terrestrial to aquatic systems will be a key next step in having a truly landscape-integrated forest carbon budget model, and calls for a net watershed exchange or watershed-based carbon accounting approach[26]. Not accounting for these lateral carbon losses can lead to overestimating the forest ecosystem sink and underestimating that of aquatic ecosystems, particularly in boreal forest landscapes. The fate of these lateral fluxes of carbon can be emissions in the form of carbon dioxide and methane or storage in lake sediments and wetlands, which are less susceptible to disturbances. Over the last decade, the importance of aquatic systems in carbon budgets has been recognized. However, challenges remain in estimating lateral fluxes and separating terrestrial-derived versus aquatic-derived components of carbon emitted from aquatic systems.

Vision: Monitoring at long-term forest watershed studies will provide decadal measurements of lateral (riverine and groundwater) carbon export. Frameworks will be developed to track lateral carbon flows from uplands to aquatic systems at catchment scales that incorporate high-resolution digital elevation models to estimate hydrologic flows and subsequent carbon loss or accumulation within the landscape.

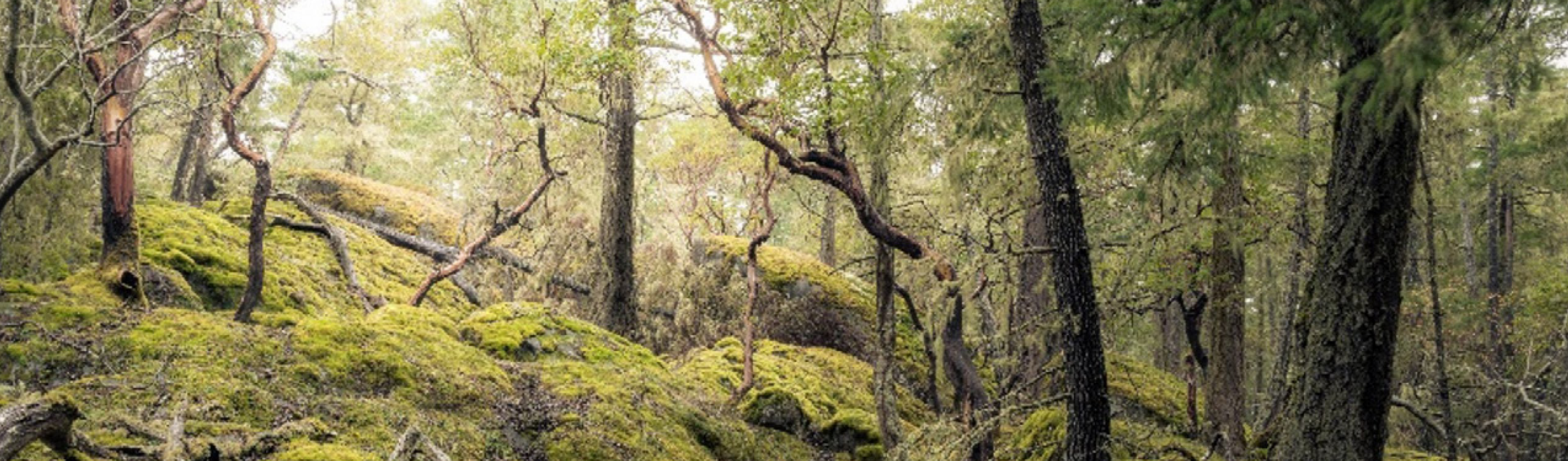
GOAL 10: Understand and predict changes in natural disturbance regimes in a changing climate, and impacts on carbon pools, transfers, and fluxes.

Climate change can increase the occurrence and severity of natural disturbances such as wildland fires and insect infestations. It is important to estimate the impact of rare but large and intense natural disturbances, the recurrence of these events, and their interactions. For example, fire weather conditions are likely to become more severe in the future for many regions, resulting in more severe wildfires and greater burned area. In 2023, wildfires reached an unprecedented high, with the largest recorded area burned in Canada: 18.5 million hectares (Mha) burned, for which 7.3 Mha was within the full response zone. Insect infestations are also shifting under changing climate conditions, which can increase the risk of damage from existing pests, shift their range (e.g., Mountain Pine Beetle and Spruce Budworm), and increase the risk of new pests. There is a critical need to understand how disturbance regimes will be affected by a changing climate[27].

Many remote sensing initiatives have been undertaken to better map the extent of historical disturbances and to track current ones, both in terms of area and severity (e.g., National Burned Area Composite for fire). Other methods have also been used to understand changes in disturbance frequency. For example, tree-ring proxies have also been used to reconstruct the past population dynamics of insects as well as drought and fire frequencies over decades to centuries regionally within Canada[28,29]. In addition, climate-sensitive process-based models have been used for studying interactions among disturbance types[30].

Natural disturbances (e.g., fire, insects, ice storms, wind) in combination with anthropogenic disturbances (e.g., forest management, mineral and oil and gas exploration and development; see Theme 1) cause large changes in the storage, transfers, and fluxes of carbon. At a landscape scale, forests are cumulatively impacted by natural and anthropogenic disturbances, including changes in climate and other environmental stressors such as atmospheric deposition of pollutants. Work over the last decade has shown that the spatial and time scales of impact and recovery differ among these stressors and that the impacts of one disturbance may exacerbate or offset the impacts of another stressor.

Vision: National assessments of disturbed area and severity by disturbance type will be developed and combined with models and field studies to assess impacts on carbon pools, transfers, and fluxes. Models of climate-sensitive disturbance occurrence and intensity will be developed that support long-term (multi-decadal) forecasting, and integrated models will be developed that quantify the impacts of individual disturbances and cumulative effects of multiple disturbances on carbon dynamics.



Theme 3. Climate change mitigation opportunities in the forest sector

Under the Paris Agreement, the UNFCCC has specified that "Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1(d), of the Convention, including forests" and implement and support policy approaches thereby "reducing emissions from deforestation and forest degradation, and [supporting] the role of conservation, sustainable management of forests and enhancement of forest carbon stocks…"[2]. Globally, it is recognized that forests and peatlands can contribute towards mitigating climate change[31] in addition to providing a wealth of other benefits for the environment, biodiversity, and society.

In the last 10 years, the Government of Canada and the provinces and territories have implemented several forest- and wood product-based climate change mitigation measures. These measures were informed by Canadian scientific research on the carbon impact, cost, and feasibility of options for forest-based mitigation. Implemented programs include the federal 2 Billion Trees program, B.C.'s Forest Carbon Initiative, Ontario's 50 Million Tree Program, and sectoral incentive programs such as Green Construction through Wood (GCWood) and similar programs in B.C., Ontario, Quebec, and the Atlantic provinces, as well as Clean Energy for Rural and Remote Communities Programs. These programs are multi-year initiatives aligned with national and international commitments and demonstrate accountability through reporting requirements.

Our understanding of the forest-related mitigation potential in Canada has increased substantially over the past 10 years. Studies have identified that the best approaches can vary by region, reflecting the diversity of climate and ecological conditions and management practices, and that some activities can be counter-productive[32–34]. Mitigation efforts involving the forest sector can be aimed at reducing GHG emissions from forest activities, maintaining or increasing carbon stocks in the forest and in harvested wood products, reducing emissions through the use of these products instead of more emissions-intensive materials or fossil fuel burning (substitution benefits), and better managing the recycling and end-of-life of materials. The timing and magnitude of GHG reductions can differ greatly among mitigation options, and a portfolio approach can maximize the benefits.

Climate change mitigation research can be expanded to support policy choices and strategic and operational decisions about activity implementation that include environmental, economic, and social dimensions, with strategies for including biodiversity and climate change adaptation goals. Carefully planned mitigation activities apply the best available science to ensure optimal adaptation for each situation and location, avoiding unintentionally intensifying climate-related risks to biodiversity and human well-being[35]. Connecting carbon to other values is an integral part of implementation, including the concept of nature-based solutions, as discussed in Theme 5.

GOAL 11: Identify climate change mitigation opportunities involving forest management, including adaptation measures and natural disturbance management options.

Evaluating climate change mitigation options in the forest sector involves producing a comparative assessment with national coverage of regionally differentiated forest management options, compared to a forward-looking baseline, with consideration of future disturbance risks, climate change impacts, and policy- and market-mediated effects, among others. This requires the best available estimates of forest carbon dynamics and accumulation at the tree and stand level.

Mitigation options in the forest sector include reducing harvest levels and/or extending harvest ages, switching from clear-cut to partial harvest, changing species composition and mixture, managing stand density through pre-commercial or commercial thinnings, managing harvest residues, reducing site preparation emissions, enhancing soil carbon, restoring forests after natural disturbances, enhancing growth through fertilization or mechanical control, and salvage harvesting in lieu of live-tree harvesting.

Mitigation options in the forest ecosystem require a comparison against a forward-looking baseline that is often a projected "business as usual" scenario. The choice of baseline can make an important difference in the timing and potential for mitigation due to assumed climate change impacts, forest age and species characteristics, and assumed disturbance rates. Projections of disturbance risk need to consider spatial variability of the landscape, ecosystem dynamics, and climate change effects on both the disturbance (e.g., area burned) and the resulting ecosystem dynamics. For example, conservation projects that reduce harvest levels may or may not result in GHG reductions depending on the initial forest age-class structure, future growth and disturbance risks, as well as wood use and substitution benefit assumptions. We discuss wood use and substitution in Goal 13.

Adaptation measures are also included in mitigation options through selection of adapted tree species from breeding programs that increase forest resilience. In areas with high risk of future wildfires, pests, or high mortality due to climate change impacts, mitigation potential relies on combining ecosystem-based activities with adaptive forest management to reduce emissions from disturbances and reduce risks. GHG reduction can often be site specific in terms of impact and duration, especially for soil carbon[36], and better estimates and measurements are necessary for long-term impact evaluation.

Vision: Canada's climate change mitigation programs involving the forest sector will be supported by expanded comparative assessments of management options that are regionally differentiated, relative to a forward-looking baseline, and based on the best available data and methods for quantifying forest carbon at the tree, stand, and landscape level. Analyses will include impacts of climate change and future disturbance risks, sensitivity assessments, and adaptation- and natural disturbance-based forest management.

GOAL 12: Identify climate change mitigation opportunities involving afforestation, reduced deforestation, restoration, and reclamation.

Mitigation options involving land use change include afforestation (establishing a forest on land that was not previously forested) and avoided deforestation. For afforestation, the rate of carbon accumulation uptake is strongly dependent on past land use, soil type, climate, and tree growth and survival rates[37]. Carbon accumulation is subject to large uncertainties, especially for soil and litter. Afforestation needs to consider changes in evapotranspiration and albedo, which can have important effects on the climate system. For example, changes in forest cover can change the extent to which incoming solar radiation is reflected back to the atmosphere, thereby affecting warming.

The risk of maladaptation is an important consideration for afforestation and reforestation activities. Incorporating vulnerability analysis, risk analysis, and adaptive management into forest management can facilitate adaptation and minimize negative climate change impacts[38].

The mitigation option for avoided deforestation considers reduced forest conversion rates. The annual rate of deforestation has been declining in Canada and was ~ 49,000 hectares (ha) per year in 2021 with a projected rate of ~ 31,000 (ha) per year in 2030[39]. Deforestation does not include temporary loss of forest cover due to timber harvesting or natural disturbances since these are not considered land use changes. Most deforestation occurs in agricultural, mining, and oil and gas sectors, but hydroelectric infrastructure and reservoirs and built-up areas also contribute[5]. Avoided deforestation options could include reduced conversion rates of forests to cropland assuming efficiencies in food production and changes in diet[34], reduced urban or industrial deforestation, and consideration of warming due to forest cover changes.

Mitigation options for forested peatland systems focus on avoiding disturbances and restoration. Most peatland disturbances involve drainage, resulting in immediate and persistent emissions, which can be stopped by rewetting, even if the system does not fully return to pre-disturbance conditions.

Vision: Assessments with national coverage of climate change mitigation for afforestation and avoided deforestation opportunities will be developed based on the best methods available for quantifying carbon accumulation. These assessments will be regionally differentiated and will include management to promote growth and mitigate loss and disturbance risk, in addition to including non-GHG impacts directly related to warming.

GOAL 13: Identify climate change mitigation opportunities involving wood products.

Mitigation options involving harvested wood products include lowering the overall emissions from wood products that are needed to meet society's demands and substituting high-emission products or materials with wood. Emissions from wood products consider the extraction and manufacturing emissions, product lifetime, recycling and cascading use, and post-consumer treatment. The latter can include product incineration or combustion for energy, landfill storage and emissions with potential flaring or energy recovery, and the potential of carbon capture utilization or storage.

Comparative analyses of mitigation options include lowering supply chain emissions and creating longer-lived wood products, which store carbon in the wood product for long periods and are considered a biomass carbon removal and storage (BiCRS) approach where forests have removed carbon from the atmosphere and it is stored in long-lived wood products. Generally, these products are used in the built environment, but other bioproducts such as biochemicals and biomaterials that include re-use and recycling in their design could also store carbon for long periods.

Wood that is no longer useful, harvested wood that cannot be used for wood products, or wood salvaged after natural disturbances is often burned (with or without energy capture) or put into landfills. Mitigation options include capturing energy from burning wood and avoiding fossil fuel burning, and capturing or flaring landfill emissions. Emissions from bioenergy and landfills can be reduced through carbon capture and underground storage in the future as the technologies become more reliable and the associated costs are significantly reduced.

Wood use can also be directed to create longer-lived products that specifically substitute for high-emission materials, or to bioenergy that specifically substitutes for high-emission fossil fuel burning. This substitution benefit can be considered, along with the net change in emissions in the forest ecosystem and wood product/bioenergy emissions, to estimate the overall GHG benefit of mitigation activities. Substitution benefits consider the fossil emissions associated with the product manufacturing and supply chain and are estimated from life cycle assessment tools, life cycle inventory databases, or environmental product declarations. A comprehensive understanding of the carbon consequences of wood may be obtained through improvements in these data sources, which will also support policy development because they include other environmental effects including pollution, toxicity, and effects on human health.

Vision: Assessments with national coverage of the climate change mitigation potential for wood use will be regionally differentiated, will consider all stages of a product's life cycle and substitution benefits, and will address some of the barriers to implementation.

GOAL 14: Identify climate change mitigation opportunities involving bioenergy.

Bioenergy refers to heat, electricity, or combined heat and power, biofuels, and biogas generated from anaerobic digestion and other technologies. The effectiveness of bioenergy has been debated because of the high variability in its mitigation potential, reflecting the diversity of biomass supply chains (e.g., sources, technologies) and the differing assumptions and methodologies used in analyses (e.g., different baselines, temporal and system boundaries, or assumptions of carbon neutrality).

The mitigation potential of bioenergy depends on the carbon dynamics associated with the source of the biomass itself and its carbon balance if not used for bioenergy; the supply chain emissions, including biomass harvest, transport, processing, and delivery to end users; the technological processing emissions for energy generation; the avoided emissions from the energy source that bioenergy replaces; and the potential to capture combusted carbon and utilize or store it. Mitigation estimates are sensitive to the spatial scale and time frame of assessment, market-mediated responses, the baseline projections for forest growth, harvest and natural disturbance assumptions, and fossil fuel emissions intensity.

Vision: National bioenergy GHG estimates and costs will be developed for a range of feedstock selections and regionally differentiated fossil energy assumptions. New tools will become available that use simple and practical methods for managing bioenergy projects that contribute to net-zero commitments, based on the best-available data and methods.

GOAL 15: Develop forecasting systems and model linkages that permit evaluation of baseline and scenarios of mitigation and adaptation.

Successful advancement of climate change mitigation measures will rely on knowledge and tools from all other Blueprint themes. Model predictions are the basis for assessing which mitigation or adaptation measures can be applied and their impact. However, models are a simplification of a complex system and need to be regularly improved, updated, and evaluated. Confidence in predictions needs to be assessed and improved in short time frames if mitigation measures are to be effective. Current estimation frameworks have weak model-data linkages, are challenging to reconfigure and improve, are not readily connected to other models and disciplines, and are not designed for iterative forecasting, limiting the use of data science advances and resulting in infrequent evaluations.

With nimble modelling systems, forecasting and backcasting are used to evaluate changes in baseline levels, and an array of mitigation and adaptation scenarios. These systems will be used for assessing if we are on track with our mitigation and adaptation strategies and goals.

Vision: Progress towards mitigation and adaptation goals will be tracked using transparent, flexible, and nimble modelling systems that provide iterative, spatially explicit forecasts of mitigation scenarios. Forecasts will be constantly updated and evaluated as new data and science become available and are integrated in the modelling system.

Theme 4. Indigenous perspectives and traditional knowledge

"Indigenous knowledge and western science are independent but complementary tools of discovery. Each uses observation, data collection, and logic to make sense of the world"—Canadian Wildland Fire Research Blueprint

Since the 2012 Forest Carbon Blueprint, Canadian society has been shaped by major events such as the publication of the Truth and Reconciliation Commission's (TRC) final report and 94 Calls to Action, and adoption of Bill C-15: *An Act respecting the United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP) in 2021. The TRC defined reconciliation as "an ongoing process of establishing and maintaining respectful relationships" (TRC, 2015, p. 121). The TRC has called upon the Canadian civil service to educate itself about the history and impact of residential schools, UNDRIP, treaties and Aboriginal rights, Indigenous law, and Aboriginal-Crown relations. In addition, Justice Canada outlined principles for Government of Canada relationships with Indigenous peoples in 2017 (Box 4).

For millennia, forests have been part of a larger reciprocal relationship between Indigenous Peoples and the land. In the past decade, Indigenous voices have frequently advocated to protect Canada's forests and for a holistic approach to forest management. Indigenous Protected and Conserved Areas (IPCAs) and the Indigenous Guardians program in Canada represent a modern recognition of the importance of Indigenous land stewardship and Indigenous rights. The Indigenous Circle of Experts was formed to make recommendations and offer guidance on how IPCAs could be realized in Canada and contribute towards Canada's conservation goals. The IPCA framework is holistic, reflecting conservation that includes people and culture[40].

BOX 4: Ten Principles respecting the Government of Canada's relationship with Indigenous Peoples

1. All relations with Indigenous peoples need to be based on the recognition and implementation of their right to self-determination, including the inherent right of self-government.
2. Reconciliation is a fundamental purpose of section 35 of the Constitution Act, 1982.
3. The honour of the Crown guides the conduct of the Crown in all of its dealings with Indigenous Peoples.
4. Indigenous self-government is part of Canada's evolving system of cooperative federalism and distinct orders of government.
5. Treaties, agreements, and other constructive arrangements between Indigenous Peoples and the Crown have been and are intended to be acts of reconciliation based on mutual recognition and respect.
6. Meaningful engagement with Indigenous Peoples aims to secure their free, prior and informed consent when Canada proposes to take actions which impact them and their rights on their lands, territories, and resources.
7. Respecting and implementing rights is essential and that any infringement of section 35 rights must by law meet a high threshold of justification, which includes Indigenous perspectives and satisfies the Crown's fiduciary obligations.
8. Reconciliation and self-government require a renewed fiscal relationship, developed in collaboration with Indigenous nations, that promotes a mutually supportive climate for economic partnership and resource development.
9. Reconciliation is an ongoing process that occurs in the context of evolving Indigenous-Crown relationships.
10. A distinctions-based approach is needed to ensure that the unique rights, interests and circumstances of First Nations, the Métis and Inuit are acknowledged, affirmed, and implemented.

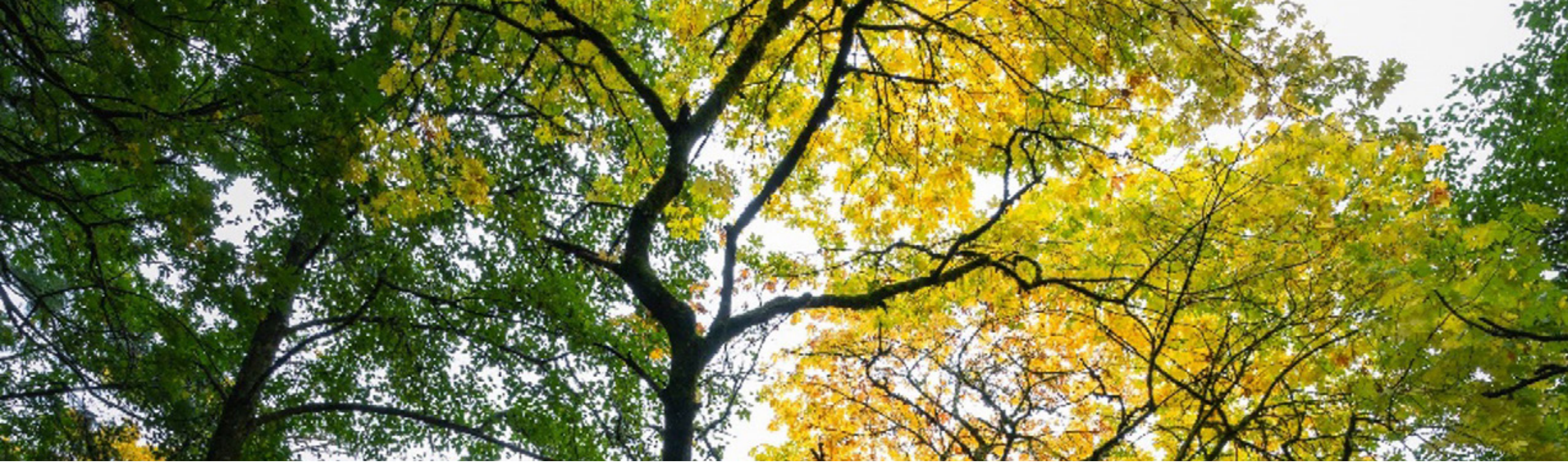
Government of Canada (2017). Principles Respecting the Government of Canada's Relationship with Indigenous Peoples. ISBN 978-0-660-25093-9 https://www.justice.gc.ca/eng/csj-sjc/principles-principes.html [accessed Jan. 19, 2023.]

As a result of these historic events, and through Indigenous leadership, the forest carbon community is broadened through reciprocal cooperative activities where we can learn together while respecting Treaty and UNDRIP obligations, responding to TRC Calls to Action, and managing data related to research by and with Indigenous groups in accordance with principles developed and approved by Indigenous groups, and on the basis of free, prior, and informed consent.

GOAL 16: Improve understanding of forest carbon through Indigenous-led research that is centred on Indigenous voices and experiences and application of Indigenous Knowledge systems.

Forest carbon research, like other research, takes place on Indigenous land, and national GHG assessments use and analyze data collected in the field, or with remote sensing approaches, on the traditional and current lands of Indigenous Peoples. Advancing reconciliation in forest carbon science could include Indigenous leadership in forest stewardship and economic development, and can be centred on Indigenous voices in project goals and methods from the outset.

Vision: TRC Calls to Action and Bill C-15 implementation will be reflected in forest carbon scientific research, bringing in Indigenous voices as an essential component and recognizing that Indigenous Knowledges and western approaches are both important, are both needed, and require significant changes to research practices and collaborations to be respectful to Indigenous Peoples and Indigenous methodologies. Understanding of Indigenous Methodologies, protocols, and knowledge in forest carbon research priorities, goals, and actions will be advanced through authentic and respectful Indigenous engagement with national Indigenous organizations, and under the guidance of Indigenous partners.



Theme 5. Connecting forest carbon to other values

The fifth Blueprint theme responds to a heightened need to connect carbon to other social, cultural, and economic values, to connect forest carbon scientists, and to communicate forest carbon science. Communication, collaboration, and interdisciplinary approaches will be essential to respond to multiple, simultaneous policy imperatives, to maximize uptake of the Blueprint, and to receive support from the public and private sectors. Responding to global biodiversity and climate change imperatives requires mobilizing our collective expertise, knowledge, and capacity.

Understanding social values linked to forest carbon calls for interdisciplinary and multidisciplinary approaches, which are embedded in Canada in a context of reconciliation. This last theme promotes a holistic understanding of forest carbon that includes natural/physical science, social, economic, and technical disciplines, Traditional Knowledges, and explicit expansion of forest carbon assessments to include other forest ecosystem services, such as biodiversity, clean water, and human well-being.

GOAL 17: Advance understanding of the broader impacts of Nature-based Solutions to climate change.

Nature-based Solutions (NbS) gained policy momentum around 2018 to address interconnected global challenges such as climate change and biodiversity loss. Although there is no universally agreed or legal definition of NbS, Canada and many other countries support the United Nations Environment Assembly (UNEA) definition: "*Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits*"[42].

In 2019, Canada announced its commitment to advance Nature-based Solutions to fight climate change. Since then, several federal departments have advanced a joint Natural Climate Solutions Fund (NCSF), which includes the 2 Billion Trees program (NRCan), Agricultural Climate Solutions (Agriculture and Agrifood Canada (AAFC)), and Nature Smart Climate Solutions Fund (ECCC). In addition to assessing carbon benefits, assessing the co-benefits of NbS initiatives is important. For example, increased tree cover has been associated with co-benefits linked to biodiversity, climate adaptation, and mitigation of urban heat-island effects[43]. As a relatively new concept, NbS initiatives in Canada require rapid advances in scientific research to support effective implementation.

Social science research has explored community reactions to forest-based carbon credit programs and forest-based bioenergy and has considered future environmental and social challenges while implementing climate change mitigation and biodiversity programming. A critical factor for NbS implementation is related to land tenure and rights, particularly those of Indigenous Peoples whose territories encompass opportunities for NbS. "Indigenous-led [natural climate solutions] provide an opportunity for reconciliation and reliance on time-proven and effective approaches for land stewardship and biodiversity conservation"[34], and provide opportunities for building skills in research rooted in reconciliation, participation, and consent. Figure 1 illustrates multiple policy goals addressed as part of NbS.

Vision: Forest carbon science will be integrated into well-balanced qualitative and quantitative evidence to advance the full range of NbS benefits, including human well-being, clean water, and biodiversity. Forest carbon science will better reflect links between forest carbon and human well-being through a reconciliation lens.

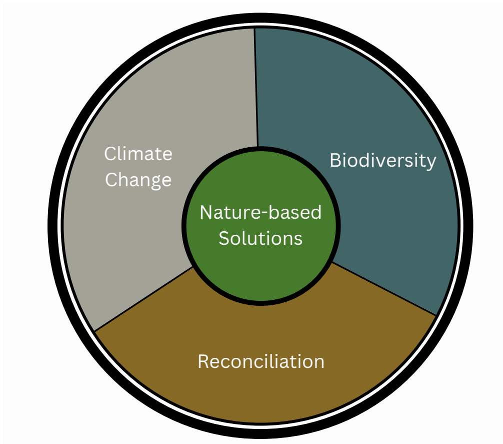


Figure 1. Nature-based Solutions provide multiple benefits, including decreasing GHG emissions, supporting biodiversity and wildlife habitat, and advancing reconciliation with Indigenous peoples.

GOAL 18: Advance interdisciplinary and multidisciplinary approaches to forest carbon science.

"You know me as carbon. You think you know me. But do you?" [(Carbon: The Unauthorized Biography)]

Recent, major international conservation commitments will influence the next decade of forest carbon research and enhance interdisciplinary approaches. The Kunming-Montreal Global Biodiversity Framework[44], ratified in 2022, set a goal of 30% of the planet as protected spaces by 2030, and the adoption of Systematic Conservation Planning (SCP) under the Convention of Biological Diversity will require monitoring biodiversity progress. Tracking conservation areas and biodiversity simultaneously to respond to habitat loss will also shape forest carbon research.

Human health and economic well-being depend on the health of ecosystems and species. Natural disturbances can cause wide-ranging impacts affecting human health and safety, community and ecosystem resilience, and the bioeconomy. Activities to support climate mitigation affect a myriad of values, including ecological values such as biodiversity and ecosystem functions, economic values in terms of jobs and tourism, resource values in terms of timber, pulp, and higher value bioproducts, health values in terms of clean water and air, and mental health and social values in terms of recreation, education, cultural practices, and spiritual beliefs. Understanding these diverse values requires using multidisciplinary and interdisciplinary approaches.

Multidisciplinary research is where different research specialists work independently, whereas interdisciplinary research is a mode of research that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines to advance fundamental understanding or to solve problems whose solutions lie beyond the scope of a single discipline. Multidisciplinary and interdisciplinary approaches will enable the forest carbon science community to respond to shifting expectations regarding forest carbon and biodiversity programs, and to report regularly and transparently. Equally important, the commitment of Canadians to the Truth and Reconciliation Commission's Calls to Action will continue to transform Canadian society and forest carbon science.

Vision: The forest carbon community will collaborate across disciplines to effectively and efficiently respond to emerging information needs and shifting expectations regarding other values, including commitments to Indigenous rights and reconciliation and biodiversity. Use of approaches that understand a range of values will enable multiple ways to implement forest carbon-based climate solutions.

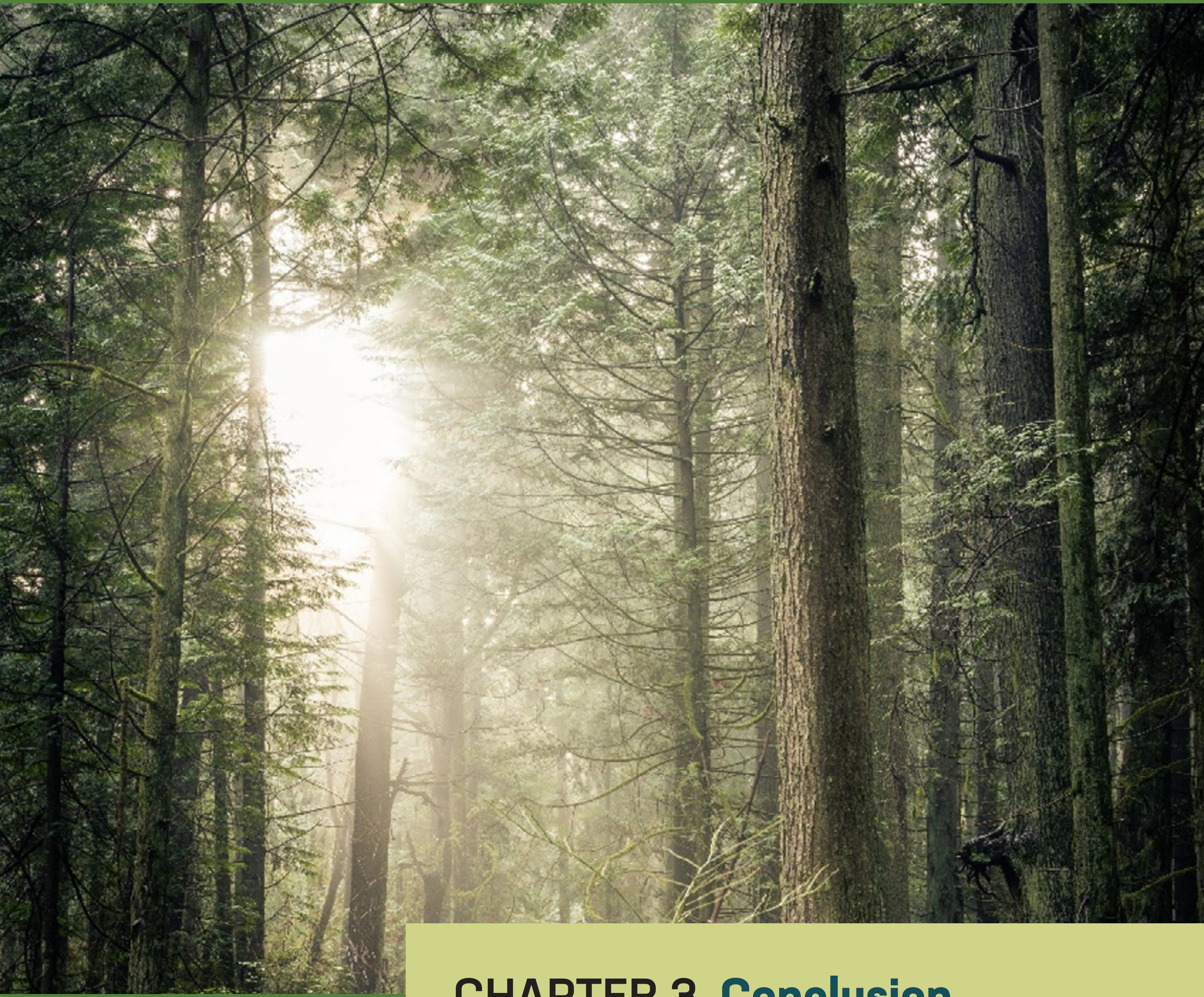
GOAL 19: Improve communication of forest carbon modelling and research.

Forest carbon is within a complex dynamic ecosystem and is a challenging subject to communicate effectively. Coupled with this challenge, there has been a recent increased stakeholder interest in accessing information on forest carbon and the contribution of forests towards climate change mitigation. A recent audit by the Commissioner of the Environment and Sustainable Development[45] of the Office of the Auditor General of Canada emphasized the need to improve the transparency of Canada's forest carbon reporting. There is a need to improve the communication of Canada's efforts to estimate the impacts of human actions on forest sector carbon (see Theme 1) to not only fulfill UNFCCC requirements but also domestic priorities, and to ensure transparency and confidence in the public sphere. A wide variety of outputs can be used, including timely peer-reviewed publications, multidisciplinary reports in accessible language and formats, and analysis and decision-support tools.

Trust in science depends, to some extent, on connections between scientists and the broader community[46]. Implementing two-way communication strategies rather than more passive one-way science communication is vital to building such connections[47]. Continuing efforts by the forest carbon community to provide greater transparency in approaches, data sharing, and continuous improvements in forest carbon estimation will contribute to public confidence and evidence-based decisions.

Moving forward in a spirit of reconciliation and humility while building trust and authentic relationships with internal and external collaborators, both internationally and domestically, will help unlock a broader understanding of the role of forest carbon in our health and well-being.

Vision: Forest carbon estimates and uncertainties, research findings, and information will be communicated in a way that meets the needs of Indigenous Knowledge keepers, scientists, policy-makers, land managers, stakeholders, and the public.



CHAPTER 3. Conclusion

"Today, I am presenting a plan to super-charge efforts to achieve this Climate Solidarity Pact through an all-hands-on-deck Acceleration Agenda." (UN Secretary-General António Guterres).

The Acceleration Agenda, as proposed by UN Secretary-General António Guterres, will require cooperative work integral to our common ability to respond to the existential crises of climate change and biodiversity loss, requiring "everything, everywhere, all at once." No single organization can address the full spectrum of research and knowledge needed to respond effectively to climate change and biodiversity loss. Forest carbon persists in a changing environment, affected by direct and indirect effects of climate change and human decisions about land use.

The Blueprint proposes five overarching forest carbon science-policy themes that are expected to be important for Canada over the next 10 years (Figure 2; Chapter 2). Each theme includes key research goals to support policy development and Appendix 3 discusses data and infrastructure requirements to support these research goals. We hope the Blueprint will continue to be used as a guide for scientific research across Canadian forest carbon science and policy communities.

Significant knowledge exchange efforts are required to ensure that the forest carbon goals outlined in the Blueprint effectively inform policy. As outlined throughout the Blueprint, knowledge includes many different forms, such as local and Indigenous ways of knowing. Given the complexity of forest ecosystems, there is a well-known science-policy gap in which knowledge produced is, in some cases, not used or understood for the purpose of policy development. Improved communication and collaboration between the producers and users of knowledge is key to addressing this science-policy gap and maximizing the uptake of knowledge produced. Improved collaboration across the diversity of governmental and non-governmental organizations involved in forest carbon science and policy is required, with the inclusion of Indigenous Knowledge systems being particularly vital.

To ensure improved collaboration, we propose periodic progress reviews of the Blueprint to encourage ongoing knowledge exchange across the science-policy interface and to facilitate evaluation and adjustment of science-policy themes and goals. This update cycle will ensure that the Blueprint is adapted to emerging policy needs over time and will support the Blueprint's value in guiding and maintaining a strong network of users and producers of forest carbon knowledge in Canada.

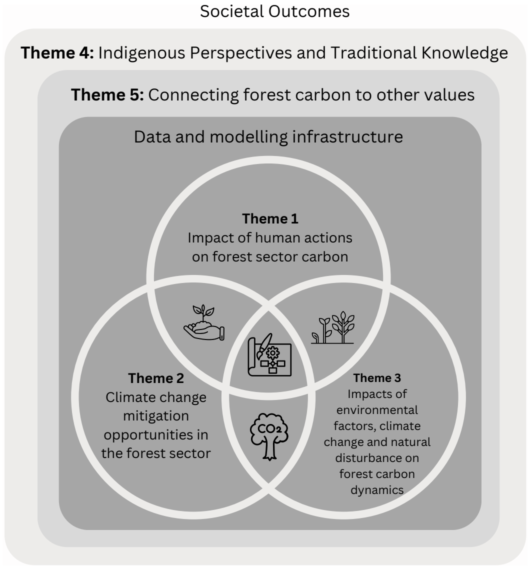


Figure 2. Schematic of the Blueprint's five overarching forest carbon science-policy themes

Abbreviations and Acronyms

3PG: Physiological Processes Predicting Growth
AAFC: Agriculture and Agri-Food Canada
BEPS: Boreal Ecosystems Productivity Simulator
C-15: Bill C-15: *An Act respecting the United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP)
CaMP: Canadian Model for Peatlands
CanFIRE: Canadian Fire Effects model
Can-IBIS: Canada-specific version of the integrated biosphere simulator
CASFRI: Common Attribute Schema for Forest Resource Inventory
CBM-CFS3: Carbon Budget Model of the Canadian Forest Sector
CCFM: Canadian Council of Forest Ministers
CCRS: Canada Centre for Remote Sensing
CFS: Canadian Forest Service
CIDET: Canadian Intersite Decomposition Experiment
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
DOC: Dissolved Organic Carbon
DOM: Dead Organic Matter
EALCO: Ecological Assimilation of Land and Climate Observations
ECCC: Environment and Climate Change Canada
ecosys: three-dimensional process-based ecosystem mathematical model
FCRN: Fluxnet-Canada Research Network
FireMARS: Fire Monitoring, Accounting and Reporting System
GCBM: Generic Carbon Budget Model
GHG: greenhouse gas
HWP: harvested wood products
ICOS: Integrated Carbon Observation System
InTEC: Integrated Terrestrial Ecosystem Carbon model
IPCC: Intergovernmental Panel on Climate Change
IPCA: Indigenous Protected and Conserved Areas
LULUC: Land Use and Land-Use Change
MAGPlot: Multi-Agency Ground Plot database
NACP: North American Carbon Program
NBP: Net Biome Productivity
NbS: Nature-based Solutions
NECB: Net Ecosystem Carbon Balance
NEE: Net Ecosystem Exchange
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
NTEMS: National Terrestrial Ecosystem Monitoring System
OERD: Office of Energy Research and Development
Ra: Autotrophic respiration
Rh: Heterotrophic respiration
SCP: Systematic Conservation Planning
SOM: Soil Organic Matter
TRC: Truth and Reconciliation Commission
UNFCCC: United Nations Framework Convention on Climate Change

Glossary

Unless otherwise indicated, the source of all definitions are taken from the IPCC.

2 Billion Trees program: Federal government program that provides financial support to organizations to plant 2 Billion trees over 10 years. https://www.canada.ca/en/campaign/2-billion-trees.html [Accessed June 7, 2023.]

3PG: Generalized forest carbon allocation model used to derive monthly estimates of gross primary productivity, carbon allocation, and stand growth. https://www.fsl.orst.edu/mycology/ss/3PG.htm [Accessed Jan. 2, 2023.]

adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

afforestation: Conversion to forest of land that historically has not contained forests.

albedo: The proportion of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage.

anthropogenic emissions: Emissions of greenhouse gases (GHGs), precursors of GHGs, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes (LULUC), livestock production, fertilization, waste management, and industrial processes.

autotrophic respiration: Respiration by living plant as photosynthates are transformed into tissues or used by plant organs such as stems, roots, and foliage when light is absent.

biochemicals: Biomass-derived chemicals that are used for a broad range of applications including chemical building blocks, additives, dyes, flavours and fragrances, lubricants, solvents, and pharmaceuticals.

biomass: Organic material excluding the material that is fossilized or embedded in geological formations. Biomass may refer to the mass of organic matter in a specific area.

biomass turnover: Annual mortality of trees or tree components (foliage, branches and fine roots) that die.

biomaterials: Biomass-derived materials that span a broad range of material properties, including composites, fibres, polymers, and resins.

BioSIM: A software tool designed to assist in the application of temperature-driven simulation models in pest management. BioSIM's main purpose is to generate forecasts of features or "events" in the seasonal biology of pests or their host plants. Forecasts are made by simulation models based on interpolated regional air temperature and precipitation adjusted for elevation and location differentials with regional gradients. BioSIM can be used to plan the deployment of sampling or surveying crews and can help time the application of pest control substances for optimal results.

Canada Centre for Remote Sensing (CCRS): Government of Canada's (Department of Natural Resources) centre of excellence for remote sensing and geodesy. CCRS operates as a division of the Canada Centre for Mapping and Earth Observation (CCMEO), conducting research and delivering remote sensing science and expertise on behalf of the Government of Canada. 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. https://www.nrcan.gc.ca/science-and-data/research-centres-and-labs/canada-centre-remote-sensing/21749 [Accessed Jan. 2, 2023.]

Canadian Fire effects Model (CanFIRE): A compilation of Canadian fire behaviour 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. https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/34093.pdf / [Accessed Jan. 2, 2023.]

Canadian Intersite Decomposition Experiment (CIDET): The Canadian Intersite Decomposition Experiment is a cooperative study of 20 researchers from the Canadian Forest Service, universities and provincial ministries investigating the long-term rates of litter decomposition and nutrient mineralization over a broad range of forested ecoclimatic regions in Canada. https://cfs.nrcan.gc.ca/projects/76 [Accessed Aug. 15, 2023.]

Canadian Land Surface Scheme (CLASS): Model of surface–atmosphere exchanges of CO_2, water vapour, 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[49]. https://cccma.gitlab.io/classic_pages/info/class/ [Accessed Jan. 2, 2023.]

Canadian Model for Peatlands (CaMP): A model for national greenhouse gas emission and removal estimation for Canadian peatlands (CaMP v2.0) Forest carbon accounting tools (canada.ca).

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 behaviour maps. In addition, satellites are used to detect fires. The CWFIS is responsible for creating daily fire weather and fire behaviour maps and hot spot maps. https://cwfis.cfs.nrcan.gc.ca/home [Accessed Jan. 2, 2023.]

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3): Stand and landscape-level modelling framework to simulate the dynamics of all forest carbon 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 carbon estimation methods outlined in the report IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003). Carbon Budget Model (canada.ca) [Accessed Jan. 2, 2023.]

carbon cycle: The flow of carbon (in gaseous, liquid, and solid forms) through the atmosphere, ocean, terrestrial biosphere, and lithosphere.

carbon model: A tool for the calculation and reporting of ecosystem carbon stocks and fluxes. Carbon 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 carbon models include empirical, inversion, and process-based models.

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). Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (noaa.gov) [Accessed Jan. 2, 2023.]

Common Attribute Schema for Forest Resource Inventory (CASFRI): repository of harmonized forest inventory datasets from provincial, territorial, federal government departments. CASFRIv5, developed in collaboration with University of Laval researchers, is hosted on the Canadian Council of Forest Ministers' data portal, the National Forest Information System (http://nfis.org).

CFS-TRenD: Database containing tree ring observations from forest ecosystems across Canada. Tree-Ring Database (canada.ca) [Accessed Jun. 1, 2023].

Clean Energy for Rural and Remote Communities: This program provides funding for renewable energy and capacity-building projects and related energy efficiency measures in Indigenous, rural and remote communities across Canada. CERRC is working to reduce the use of fossil fuels for heating and electricity by increasing the use of local renewable energy sources and energy efficiency.

climate: In a narrow sense, climate is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period 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 (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate, in a wider sense, is the state, including a statistical description, of the climate system.

ClimateNA: Application that downscales PRISM 1971–2000 gridded monthly climate normal data (800 × 800 m) to scale-free point locations. It calculates and derives monthly, seasonal, and annual climate variables for individual years and periods between 1901 and 2100. https://climatena.ca/ [Accessed Jun. 6, 2023.]

climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.

decay and decomposition: Decay is to decline in quality, while decompose is to separate or break down something into its components.

deforestation: Conversion of forest to non-forest.

Ecological Assimilation of Land and Climate Observations (EALCO): A 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 carbon and nitrogen dynamics using satellite observations. Ecosystem Modelling and Satellite Data Assimilation (canada.ca) [Accessed Jan. 13, 2023].

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. https://ecosys.ualberta.ca/ [Accessed Jun. 6, 2023].

Extensive forest management: A low investment level of management on regulated timberlands that requires initial harvest, regeneration, and final harvest.

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

Fire Monitoring, Accounting and Reporting System (FireMARS): National wildland fire carbon emissions reporting system developed by NRCan. The system is the overall structure that integrates satellite-detected hot spots with record daily fire growth, and final burned area; ground-based daily fire weather as monitored by the CWFIS; and stand-level carbon emissions and pool transfers during fires.

Fluxnet-Canada Research Network/Canadian Carbon Program Data Information System (FCRN/CCP-DIS): An accessible database storing GHG 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. Fluxnet (ornl.gov)/ [Accessed Jan. 2, 2023.]

forest/tree growth: Growth is often used synonymously with tissue expansion, while over longer periods it is the increase in live biomass. At larger temporal and spatial scales, growth is mostly described as net primary production (e.g., https://doi.org/10.1111/nph.17610).

forest/tree production: Live (wood) biomass increment (growth) plus annual biomass turnover plus recruitment of new trees minus tree mortality.

forest sector: The forest sector is the combination of forests and forestry industries that produce harvested wood products and bioenergy, and thus forest sector carbon includes forest ecosystem and wood product carbon.

Generic Carbon Budget Model (GCBM): The Generic Carbon Budget Model is an open source, spatially explicit, stand and landscape-level modelling framework. Similar to CBM-CFS3, GCBM is a stand and landscape-level modelling framework that simulates the dynamics of all forest carbon stocks required under the United Nations Framework Convention on Climate Change (aboveground biomass, belowground biomass, litter, dead wood, and soil organic carbon). It is compliant with the carbon estimation methods outlined in the report IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003). Generic Carbon Budget Model (canada.ca) [Accessed Jun. 6, 2023.]

Green Construction through Wood (GCWood): Federal government program that encourages the greater use of wood in construction projects and supports Canada's transition to a low-carbon economy. Green Construction through Wood (GCWood) Program (canada.ca) [Accessed Jun. 7, 2023.]

greenhouse gas (GHG): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's ocean and land surfaces, by the atmosphere itself, and by clouds.

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. Forest carbon accounting tools (canada.ca) [Accessed Jan. 2, 2023.]

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

Indigenous Data: Refers to Knowledge, information, and data, "in any format, that impact Indigenous Peoples, Nations, and communities at the collective and/or individual levels; data about their resources and environments, data about them as Individuals, and data about them as collectives." (e.g., https://doi.org/10.1038/s41597-021-00892-0).

Indigenous Knowledge Systems: Systems are each First Nation, Inuit and Métis community's "cumulative body of knowledge, practices, and beliefs, evolving and governed by adaptive processes and handed down and across generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (e.g., https://doi.org/10.1016/j.cosust.2014.11.002). Other common terms for Indigenous Knowledge include traditional knowledge, traditional ecological or environmental knowledge, Aboriginal traditional knowledge, Métis Traditional Knowledge, and Inuit Qaujimajatuqangit.

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 behaviour of the global carbon cycle and greenhouse gas emissions; and (2) to monitor and assess the effectiveness of carbon sequestration and/or greenhouse-gases emission reduction activities on global atmospheric composition levels, including attribution of emissions and removals by region and sector. https://www.icos-cp.eu/ [Accessed Jan. 2, 2023.]

Integrated Terrestrial Ecosystem Carbon Model (InTEC): Model that integrates the impacts of disturbances, management practices, climatic factors, and atmospheric factors, and estimates their effects on the annual carbon cycle of a forest region. InTEC is based on the Farquhar's leaf photosynthesis model, the Century carbon cycle model for soil carbon modelling, the net nitrogen mineralization model, and an age-net primary productivity relationship derived from forestry inventory-based age-biomass relationships. J. Chen's Research (utoronto.ca) [Accessed Jan. 2, 2023.]

intensive forest management: Utilization of a wide variety of silvicultural practices, such as planting, thinning, fertilization, harvesting, and genetic improvement, to increase the capability of the forest to produce fibre.

LANDSAT: A series of Earth-observing satellite missions jointly managed by NASA and the U.S. Geological Survey, beginning in 1972 and now operating Landsat 9.

Land Use and Land-Use Change (LULUC): The total of arrangements, activities and inputs applied to a parcel of land. 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, conservation and city dwelling). In national greenhouse gas (GHG) inventories, land use is classified according to the IPCC land-use categories of forest land, cropland, grassland, wetlands, settlements and other lands. Land-Use Change refers to the permanent change from one land-use category to another. Note that, in some scientific literature, land-use change encompasses changes in land-use categories as well as changes in land management.

maladaptation: Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence. IPCC 6th Assessment Report, https://www.ipcc.ch/report/ar6/wg2/.

MAGPlot: Multi-Agency Ground plot (MAGPlot) database which includes standardized provincial and territorial forest inventory plot data.

mitigation: In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example renewable energy technologies, waste minimization processes and public transport commuting practices. With respect to climate change, a human intervention to reduce emissions or enhance the removal of greenhouse gases from the atmosphere.

Moss Carbon Extension and Module (MOSS-C): The MOSS-C simulates the flow of carbon from the growth of live biomass through to the decomposition of dead moss litter and development of peat. Module for CBM-CFS3 or GCBM. Moss carbon extension and module (canada.ca) [Accessed Jun. 7, 2023.]

National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS): Canada's forest carbon reporting system aims to estimate forest carbon 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 carbon stocks and to predict, based on scenarios of future disturbance rates and management actions, changes in carbon stocks. Canada's forest carbon reporting system [Accessed Jan. 2, 2023.]

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 Jan. 2, 2023.]

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/en/ [Accessed Jan. 2, 2023.]

National Forestry Database (NFD): A collaborative partnership between the federal and provincial governments that aims to describe forest management and its impact on the forest resource; to develop a public information program based on the database; and 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/en/index.php [Accessed Jan. 2, 2023.]

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. https://www.noaa.gov/ [Accessed Jan. 2, 2023.]

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. https://www.nserc-crsng.gc.ca/index_eng.asp [Accessed Jan. 2, 2023.]

Net Biome Productivity (NBP) and Net Ecosystem Carbon Balance (NECB): Net ecosystem productivity (NEP) minus exports of carbon due to fire, harvest, and transport of dissolved organic carbon 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.

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 carbon from the atmosphere while negative values indicate that the ecosystem is losing carbon to the atmosphere. It is the difference between gross ecosystem photosynthesis (GEP) (or gross primary productivity, GPP) and ecosystem respiration (Re= Ra- autotrophic + Rh- heterotrophic respiration), that is, NEP=GEP−Re. It is also equal to net primary productivity minus heterotrophic respiration.

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 plant (autotrophic) respiration which releases part of the carbon absorbed, that is, NPP = Photosynthesis Rate− Plant Respiration Rate.

Office of Energy Research and Development (OERD): A federal program operated by Natural Resources Canada that funds research and development to ensure a sustainable energy future for Canada.

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

primary production: Primary production (PP) is the rate at which plants store energy or mass in organic matter. In terrestrial ecosystems, primary production is divided into two components: gross primary production (GPP) represents the total amount of carbon fixed by plants through photosynthesis; and net primary production (NPP) represents the amount of fixed carbon that remains after plants consume a portion for their own metabolism, which is called autotrophic respiration (Ra). The ratio of Ra to GPP is called carbon use efficiency (CUE) and is typically assumed to be about 0.5, but with large variation. Neither GPP nor Ra can be directly measured and many of the components of NPP are difficult to measure.

reforestation: Establishment of trees on non-treed land that had recent tree cover.

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

source: Any process or activity which releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere.

triplex: Generic hybrid model that simulates the key processes of forest growth and carbon cycle.

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Appendix 1: Workshop Participants and Contributors

Table A1.1 List of participants involved in the Blueprint workshops and discussions.

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Appendix 2: Survey on progress to date

A literature review was conducted to compile the number of studies and their associated citations for landscape-level peer-reviewed Canadian studies published from 2012 to 2021. Studies were categorized based on a best fit to the ten research questions posed in the 2012 Blueprint (Table A2.1).

Table A2.1 Ten research questions posed in the 2012 Blueprint and their associated science theme.

Science Theme 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 carbon dynamics from stand to national scales and from sub-annual to multidecadal time scales?
1.2	What are the impacts of climate variability, including drought, on current forest carbon dynamics from stand to national scales and from sub-annual to multidecadal time scales?
1.3	How do local processes determining current forest carbon dynamics scale up to regional and national scales?
Science Theme 2. Improved estimates of the effects of global changes on Canada's future forest carbon	
2.1	To what extent will global changes alter carbon 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 carbon budget?
Science Theme 3. Improved estimates of the impact of Canada's forests on the global climate system	
3.1	How does the influence of forest carbon 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?
Science Theme 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?

Two surveys were conducted—the first in November 2022 with Canadian Forest Service (CFS) participants where 42 responses were received and the second in February 2023 with forest carbon community participants where 60 responses were received. The survey questions asked participants to identify how much progress had been made on various research question topics, and results were compared to publication numbers[14], Figure A2.1.

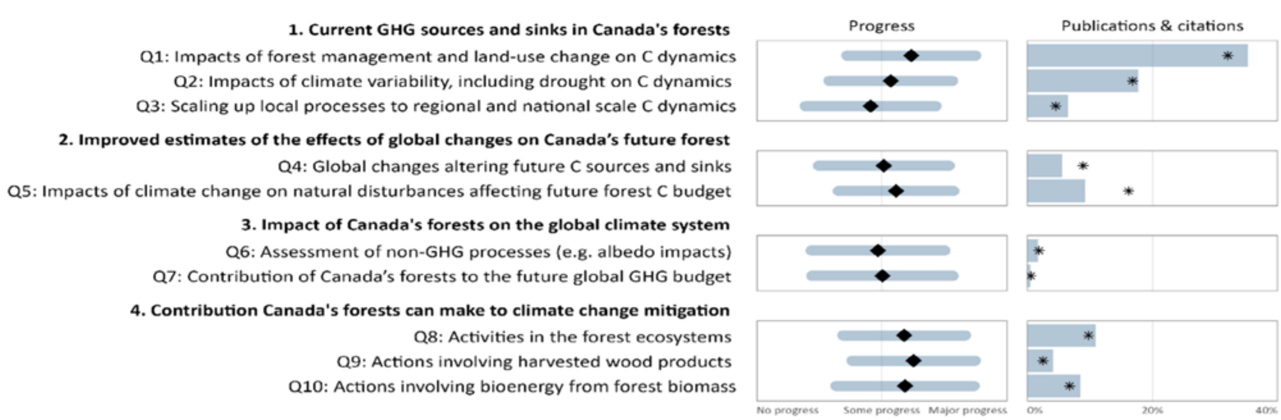

Figure A2.1 Summary of the workshop surveys on progress (average and standard deviation), and percent of total publications (bar) and associated citations (asterisk) from a 426-article literature review.

Appendix 3. Data, databases, and infrastructure

The ability to address the goals outlined in Chapter 2 relies on scientific research and monitoring activities and the integration of the results of such activities into analyses and models. This appendix surveys data acquisition and monitoring and data storage and distribution, and can be expanded to include Indigenous Knowledge.

Forest inventories, field studies, and long-term monitoring

Forest inventories provide basic information about forest attributes over time (e.g., area, age, species composition, diameter at breast height [DBH], height, site quality, and defects). 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) provides forest and land cover information from a sampling grid of ground plots co-located with remote sensing plots (i.e., photo plots) covering Canada's entire land base. The generation of a long time series of measurements contributes to the detection and quantification of global change impacts and is of great value for model parameterization and remeasurements. A national standardized plot network with ground-plot measurements in regular 5- or 10-year intervals enables the detection and reporting of forest carbon stock changes and is essential for the verification of model predictions and calibration and validation of remotely sensed products.

Field studies generate basic information and knowledge needed for model development and testing and ground-truthing remote sensing estimates. Field studies encompass a range of activities such as stand or plot-level monitoring to understand how carbon dynamics vary over space (transect studies across landscape gradients) and time (chronosequence studies). Field studies may also employ retrospective or reconstruction approaches, such as the collection of tree cores or sediment cores to examine historical patterns and climate responses. Field studies may also include manipulative experiments to quantify ecosystem responses to different experimental treatments (e.g., warming, intensity of disturbance).

Long-term monitoring of the whole ecosystem (i.e., atmosphere, soil, vegetation, and water components of the carbon cycle) across plot- to watershed-scales is needed to understand trends and ecosystem responses over longer time intervals to identify possible threshold or tipping points with changing climate and disturbance. These long-term monitoring sites can be coupled with additional field studies and experiments to put shorter-term studies into a longer-term context. A nested spatial design from plot to larger spatial units (e.g., catchment and watershed basin) is crucial for predicting integrated carbon responses and transfers across the landscape (e.g., upland forest, peatlands, streams, lakes). Long-term ecological research network at watershed scales is needed to advance understanding of scaling carbon cycling processes across the landscape.

Climate data

Climate scenarios are used in GHG model projections and allow for a range of possible futures and future risks for low-probability, high-impact, or worst-case scenarios. The Shared Socioeconomic Pathways (SSPs) correspond to the five levels of alternative socioeconomic developments[16]. For each pathway, multiple climate models are available, usually at large-scale resolution. Comparison studies (e.g., Coupled Model Intercomparisons) allow modellers to select various projections for their studies to represent the range of variability and consider the resulting uncertainty in their results.

One consideration is that extreme climatic events affect forest growth and mortality and are strongly influenced by fine-scale processes that are not well represented in global climate models. Specialized applications such as BioSIM (https://cfs.nrcan.gc.ca/projects/133) and ClimateNA generate forecasts to consider the seasonal biology of pests or host plants based on regional interpolated weather data and can optimize the use of pest management.

Remote sensing mapping products and GHG measurements

Remote sensing enables measurement and monitoring of carbon stocks and fluxes in forest ecosystems derived from spatial layers over large scales and at relatively fine spatial detail. The currently available (and constantly growing) range of sensors provide information on land cover, land cover change, forest disturbances, as well as a suite of forest inventory attributes including height, basal area, volume, and aboveground biomass. Repeated data acquisitions allow us to track changes of these attributes over time. Remote sensing data products cover large areas at various spatial resolutions and time intervals and can detect trends at regional to continental scales. The contribution of remote sensing to forest carbon science is increasing as technological capacity improves, and increasingly sophisticated carbon models call for more spatial data.

Satellite-based remote sensing technologies can also monitor GHGs in the atmosphere at broad spatial scales, with the concentrations reflecting the integration of net GHG exchanges from different land cover types (e.g., forest, agriculture, urban, lake, peatland). Ground-based measurements from different land cover types remain essential to reconcile carbon cycling processes within different land cover types to atmospheric concentrations. However, these satellite observations of GHGs have greatly increased data coverage, contributed to improved flux estimates, and enabled global mapping of GHG concentrations.

Databases, information systems, and infrastructure

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 National Forest Information System (NFIS) provides access to tools, maps, and data related to Canada's forests and science-based sustainable forest management practices and supports many applications such as the National Forest Inventory, the National Terrestrial Ecosystem Mapping System (NTEMS), the Canadian Forest Genetic Resources Information System, and the Long-term Research Installation Catalogue. The National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) is a system of databases, tools, and simulation models to produce national-scale estimates of carbon stocks, emissions, and removals in Canada's managed forests to meet carbon reporting needs and policy analysis.

In addition to databases and information systems, and other dedicated repositories (e.g., GitHub, GitLab, and others), the deployment of Web Application Programming Interfaces (API) is another option. It facilitates the integration of data into workflows and reduces the maintenance effort. The CFS-led climate-sensitive growth and yield modelling initiative is currently working on the deployment of such Web API[50].

Continued integration of data sources will improve the capacity to answer policy questions, help identify data gaps, and prioritize data acquisition. Canadian Geospatial Data Infrastructure (CGDI) defines the technology, standards, access systems, and protocols necessary to harmonize all of Canada's geospatial databases. Continuing to use CGDI and making data available on the internet will allow all to discover, integrate, and display this current, authoritative, and accurate information on Canada's forests. Ensuring the availability and accessibility of databases to all, and encouraging rapid dissemination of results increase scientific efficiencies, capacity, and synergy, and will contribute to better incorporation of carbon science knowledge into decision-making.